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SIGNIFICANCE AND CONTROL OF LAMELLAR TEARING OF STEEL PLATE IN THE SHIPBUILDING INDUSTRY

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SHIP STRUCTURE COMMITTEE

1979

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SSC-290

FINAL REPORT

on

Project SR-1250

"Lamellar Tearing"

SIGNIFICANCE AND CONTROL OF LAMELLAR TEARING OF STEEL PLATE IN THE SHIPBUILDING INDUSTRY

by

J. Sommella

Gibbs & Cox, Inc.

under

Department of Transportation
U. S. Coast Guard
Contract No. DOT-CG-74355-A

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U. S. Coast Guard Headquarters
Washington, D.C.
1979

II

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An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

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U.S. Coast Guard Headquarters,(G-M/82)
Washington, D.C. 20590

SR-1250
JULY 1979

The Ship Structure Committee recognized the need of evaluating available information on preventing lamellar tearing in marine structures. While the incidence of lamellar tearing in ship structures has been low, it is more common in mobile and fixed platforms of the type used in the offshore mineral exploration and production industry. Its occurrence results in costly repairs, and, in some instances, fabrication delays.

A project was undertaken to develop a guide describing the factors which contribute to and influence lamellar tearing, a review of the procedures used to determine susceptibility to lamellar tearing, and methods for post-welding detection and repair of lamellar tears. The results of this effort are contained in this report. Any comments or requests for additional copies are welcome.

Henry H. Bell
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

Lamellar tearing is a separation in the parent or base metal caused by through-thickness strains. These strains are usually induced by weld metal shrinkage under conditions of high restraint. This manual provides specific recommendations for controlling lamellar tearing in the types of steels used in the construction of ships and offshore platforms.

A brief description of the characteristics and mechanism of lamellar tearing shows that for lamellar tearing to occur there must be a critical combination of material susceptibility, and welding procedures and joint design which permit the development of high through-thickness strains. Tee (T) and corner joints, used extensively in ships and offshore structures, are the two basic joint configurations most susceptible to lamellar tearing. However, the incidence of lamellar tearing has been extremely rare in shipbuilding. The problem of lamellar tearing is considerably more significant in mobile and fixed offshore drilling platforms which use thick plates in highly restrained T- and cruciform joints.

The factors which contribute to and influence lamellar tearing are grouped into three categories: joint design, material selection and fabrication procedures. For each parameter recommendations are presented for reducing the risk of lamellar tearing. Inquiries made to the major ship classification societies indicate that the most successful and cost-effective method of preventing lamellar tearing is the use of steels with improved through-thickness (Z-direction) properties at susceptible connections. Methods for the post-welding detection and repair of lamellar tears are reviewed as are the test procedures developed to date for determining the susceptibility of steel plates to lamellar tearing.

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METRIC CONVERSION FACTORS

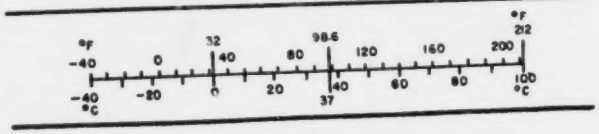
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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GLOSSARY

ANISOTROPIC - not isotropic, i.e., having different mechanical properties in different directions.

BASE METAL - the basic mill-rolled material to be welded.

COMPONENT RESTRAINT - restraint existing due to rigidity of the various elements of a joint or connection.

CONNECTION - complete assembly consisting of the various joints making up the total unit.

CONSUMABLES - the filler metal added in making a welded joint - usually in the form of electrodes or welding rods.

DECOHESION - separation along the interface between the material matrix and an inclusion.

DISCONTINUITIES - lack of homogeneous characteristics caused by nonmetallic inclusions, cracks, tears, etc.

DUCTILITY - ability of a material subjected to stress to undergo permanent deformation in the plastic range prior to rupture.

ELECTRODE STRENGTH - usually the minimum tensile strength of deposited weld material.

ELECTRODE MATCHING - the practice of providing electrode strength equal to the base metal tensile strength.

ELONGATION - percentage elongation measured in a standard tension test and used as a measure of ductility.

HEAT-AFFECTED ZONE (HAZ) - portion of the base metal adjacent to the fusion line of the weld, which is not melted but is heated during welding to a temperature high enough to modify the mechanical properties of microstructure.

INTERPASS TEMPERATURE - in multiple-pass welds, the temperature of the deposited weld metal before the next pass is started.

ISOTROPIC - having the same mechanical properties in different directions.

JOINT - junction of two or more structural members which are to be joined; a single element of a connection.

LAMELLAR TEARING - separation in the base material caused by induced strains in the through-thickness direction due to weld shrinkage.

LAMINATION - large discontinuity in rolled steel products resulting from flattening and elongating of inclusions or voids during the rolling process - usually a layer of nonmetallic inclusions.

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MATRIX MATERIAL - the major continuous substance of a metal as opposed to inclusions or particles of materials having dissimilar characteristics.

MECHANICAL PROPERTIES - tensile strength, yield stress, percentage elongation, reduction of area, etc.

MEMBER RESTRAINT - restraint in closure member where inherent rigidity requires weld shrinkage to be absorbed by the base metal.

MULTI-PASS WELDS - welds requiring more than one pass to complete deposition of required weld material.

NONMETALLIC INCLUSIONS - microscopic particles of compounds in steel matrix; principally sulfides, silicates and aluminum oxides.

PARENT METAL - the basic mill-rolled material to be welded.

PEENING - the mechanical working of the weld beads by means of light impact blows to the weld surface to reduce residual stress.

PLANAR DISCONTINUITIES - discontinuities having major dimensions of length and breadth in a plane, i.e., like a flat plate.

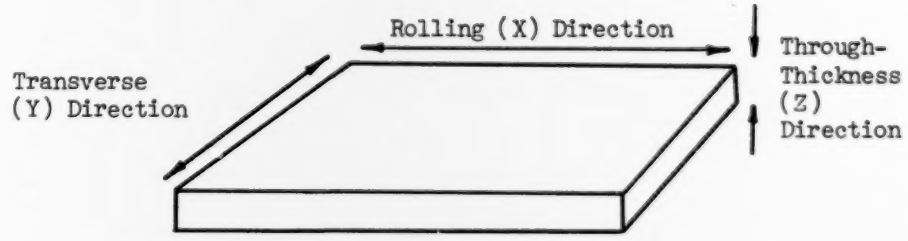
PREHEATING - the application of heat to the base metal immediately before welding.

PREPARATION - geometry of a joint detail including the edge bevel, root opening, and backup.

REDUCTION OF AREA (RA) - the maximum percentage reduction in cross-sectional area measured in a standard tension test at the point of rupture and used as a measure of ductility.

RESTRAINT - resistance of the joint or connection to movement of any kind.

ROLLING (or X) DIRECTION - direction that hot rolled structural material travels through the forming rolls - or the principal rolling direction for cross rolled material.



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STRAIN - deformation per unit of original length caused by changes in applied forces.

STRESS - force per unit of cross-sectional area.

THROUGH-THICKNESS (or Z) DIRECTION - perpendicular to the plane of the rolled surface.

TRANSVERSE (or Y) DIRECTION - perpendicular to the rolling direction in the plane of the material.

WELDING PROCEDURE - the detailed elements of welding (usually a written procedure) which define the process, voltage, current, speed, electrode type and size, position, edge preparation, preheat, sequence and any other related factors required for an acceptable weld.

WELDING SEQUENCE - the order in which welds are made in a particular weldment to minimize distortion, to compensate for shrinkage and to reduce internal stresses.

ULTIMATE STRESS - maximum stress attained before rupture of the material.

UT MATERIAL - material ultrasonically inspected in its entirety prior to fabrication.

YIELD POINT - the point on a stress-strain curve where elongation occurs with very little increase in stress.

LIST OF ABBREVIATIONS

HAZ	-	heat-affected zone
LT	-	lamellar tearing
RAz	-	percentage reduction of area in the Z direction
UT	-	ultrasonic testing

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Our ref: TGD/WH/50

9th January, 1979.

Mr. J. Sommella,
Gibbs and Cox Inc.,
40 Rector Street,
New York 10006,
USA.

Dear Mr. Sommella,

Dr. Dolby has asked me to reply to your letter concerning the report "Significance and Control of Lamellar Tearing of Steel Plate in the Shipbuilding Industry." We feel you should be congratulated on having drawn the published material together very well and produced a readable document which clears up a number of common misunderstandings (e.g. the distinction between a lamination and a lamellar tear), and gives sound advice on avoidance and repairs of lamellar tearing. We thus have no objection to your use of some of our material in your manual in its present form.

Yours sincerely,

T. G. Davey.

T.G. DAVEY
Materials Department.

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AUSTRALIAN WELDING RESEARCH ASSOCIATION
118 ALFRED STREET, MILSONS POINT, N.S.W. 2061 TELEPHONE 922-3711

AV:pd 397/62

8th December, 1978

Mr J. Sommella
Gibbs & Cox Inc.
40 Rector Street
NEW YORK N.Y. 10006

Dear Mr Sommella

18521 - Significance and Control of Lamellar Tearing of Steel Plates in the Shipbuilding Industry - SSC Project No. SR-250

Thank you for the copy of the above document which I perused with interest.

I am happy to give you formal authorisation to include the material reproduced from AWRA Technical Note 6, on behalf of the Association.

Yours sincerely,

Dr A. Vetters
DIRECTOR

XIII BEST DOCUMENT AVAILABLE

NOTES

1. INTRODUCTION

Lamellar tearing is a separation in the parent or base metal caused by through-thickness strains. Such strains are induced primarily by weld metal shrinkage under conditions of high restraint. While the lamellar tearing phenomenon has been recognized by welding experts for over thirty years, the incidence of lamellar tearing in shipbuilding has been extremely rare for ships under construction or in service. The low rate of occurrence should not belie the fact that lamellar tearing can be a potentially significant problem when it occurs in critical connections. The incidence of lamellar tearing is considerably more significant in mobile and fixed offshore drilling platforms. These are complex structures which use thick plates in highly restrained T and cruciform joints.

Where detected, lamellar tearing can result in often difficult and costly repairs and subsequent construction delays. With the proper selection of joint designs, materials, and welding procedures, the occurrence of lamellar tearing can be minimized and controlled. The intent of this manual is to provide the engineer or designer with specific recommendations for controlling lamellar tearing in the types of steels used in the construction of ships and offshore platforms. A brief description of the characteristics and mechanism of lamellar tearing is provided to give a basic understanding of the complexities of the problem and the rationale for the subsequent recommendations for its prevention. Methods of detecting and repairing lamellar tears after welding are also presented.

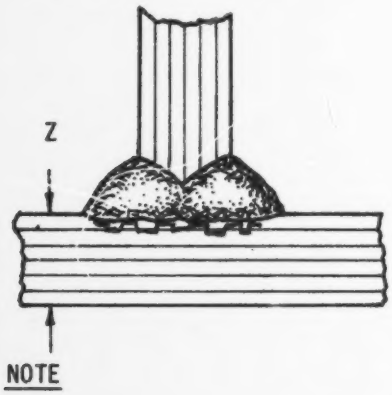
The following organizations have generously provided data on their experience with lamellar tearing and methods for its control:

- American Bureau of Shipping
- Bureau Veritas
- Det Norske Veritas
- Germanisher Lloyd
- Lloyd's Register of Shipping
- Nippon Kaji Kyokai
- Avondale Shipyards, Inc.
- Continental Oil Company
- Lukens Steel Company

Most of the published literature on lamellar tearing addresses in detail the factors and mechanisms which contribute to lamellar tearing while reviewing control procedures, particularly welding techniques, in a more cursory manner. The primary exceptions to this generalization are "Technical Note 6 - Control of Lamellar Tearing" published by the Australian Welding Research Association and "Lamellar Tearing in Welded Steel Fabrication" published by The Welding Institute. With their permission portions of their previously published material has been incorporated in this manual and the excellence of their work and their generosity in permitting its use is acknowledged. Special thanks is also due the Australian Welding Research Association for permitting the reproduction in this manual of Appendices A and B of their Technical Note 6.

2. DESCRIPTION OF LAMELLAR TEARING (LT)

2.1 What Is Lamellar Tearing?

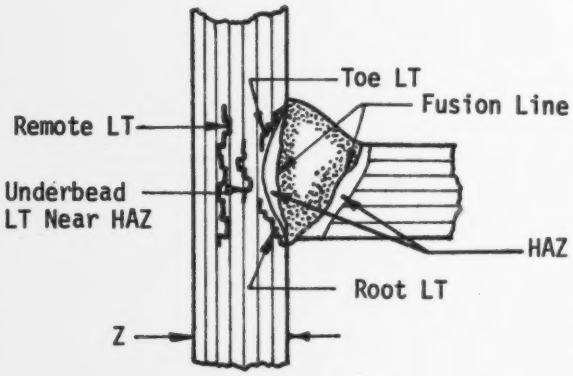


Lamellar tearing in steel fabrications is the separation of parent or base metal, primarily in planes parallel to the rolling plane of the plate, due to high through-thickness strains. The high strains in the through-thickness direction are usually induced by localized weld metal shrinkage at highly restrained joints [1].[1]

NOTE

Lamellar tearing should not be confused with "laminations" which are discontinuities in rolled steel products resulting from flattening and elongating of inclusions or voids during the rolling process.

2.2 Where Does Lamellar Tearing Occur?



The tearing always lies within the base metal, usually just outside the visible heat-affected zone (HAZ), and is generally parallel to the weld fusion boundary. The location may vary from within the lower HAZ to well into the base metal thickness. The tearing may be completely subsurface and difficult to detect or readily visible on exposed plate edges or at the toe and root of the weld.

[1]Numbers in brackets designate References in Section 9.

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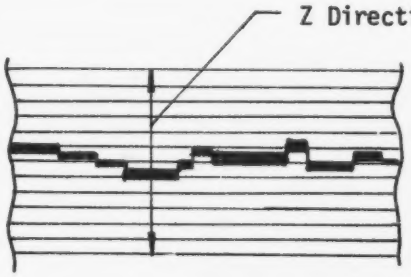
2.3 What Is The Extent of Tearing?

Lamellar tears may vary in length from a few millimeters to several meters and have a width approximately equal to the size of the weld. The thickness of the fracture may vary from a hairline crack to approximately 1 mm.

2.4 What Does A Lamellar Tear Look Like?

Lamellar tears exhibit unique appearance characteristics which enable them to be distinguished from other forms of cracking, including cracks in the HAZ caused by hydrogen. When a tear reaches a surface or is sectioned, it generally appears as a straight line in the base metal parallel to the direction of rolling of the plate.

The cross-section is step-like with longitudinal terraces that are substantially longer than the transverse depth.

The fracture surface is fibrous or woody in appearance with little or no discoloration unless the tear is corroded or has been subject to high temperatures. The flat fibrous terraces lie parallel to the plate surface, with steps or shear walls between terraces approximately normal to the plate surface.

NOTE

The characteristic fibrous or woody appearance of the fracture surface together with the terraced profile and location within the base material distinguishes a lamellar tear from other forms of cracking.

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2.5 How Is Lamellar Tearing Normally Observed Or Detected?

Lamellar tears which propagate to the surface can be detected by visual, dye penetration and magnetic particle inspection techniques. However, since most lamellar tears are completely subsurface, these detection methods are of limited usefulness. Ultrasonic testing has been found to be the most effective method of detecting sub-surface tears. A more detailed discussion of the detection and repair of lamellar tearing is presented in Section 7.

3. FACTORS CONTRIBUTING TO LAMELLAR TEARING

3.1 Under What Conditions Does Lamellar Tearing Occur?

For lamellar tearing to occur the following three essential conditions must be satisifed:

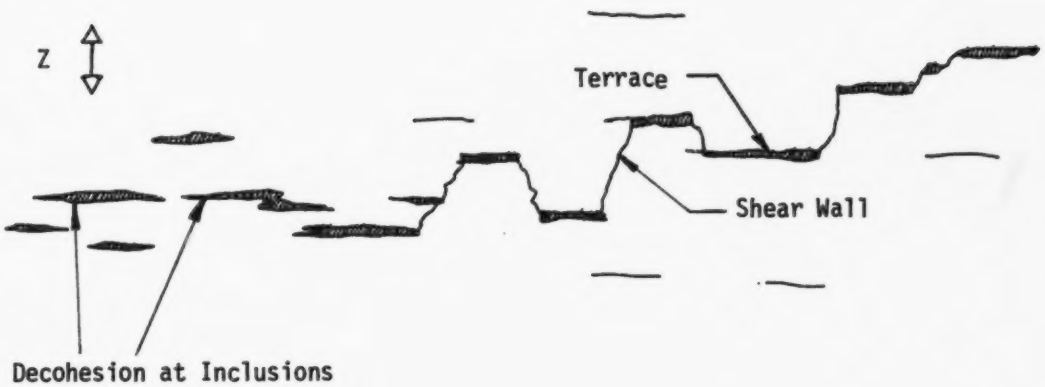
- The material must be susceptible to tearing. That is, the base material in the region of the joint must have poor ductility in the Z-(through-thickness) direction.
- The welding procedures must produce strains which act through the joint across the plate thickness, that is, through-thickness strains. Such a condition exists when the weld fusion boundary is roughly parallel to the surface of the base plate.
- The joint design must permit the development of high through-thickness strains. These strains usually result from weld metal shrinkage in the joint but can be increased by strains developed from reaction with other joints in restrained structures.

NOTE

For lamellar tearing to occur there must be a critical combination of material susceptibility, and welding procedures and joint design which permit the development of high through-thickness strains.

3.2 By What Means Does Lamellar Tearing Occur?

Lamellar tearing is generally believed to occur in three distinct phases. During the first phase voids are formed usually by decohesion or fracture of single elongated nonmetallic inclusions or groups of inclusions lying parallel to the rolling plane of the plate. Although additional void initiation mechanisms have been reported, the decohesion of microscopic inclusions is considered the primary initiation mechanism. The first phase probably takes place in the elastic range where the stress required for the initial decohesion will be dependent on the type, shape and distribution of inclusions and the properties of the material matrix.



In the second phase the initiated voids or tears on the same plane extend and join by means of necking or microvoid coalescence to form terraces. The elongation and link up of adjacent inclusions is caused by increased strains due to cooling of previously deposited weld runs and/or the depositing of additional weld metal. As the strains increase the ligaments of matrix material between the inclusions become fully plastic and the voids increase in size by ductile tearing.

Further straining in the third and final phase connects the terraces on different levels by ductile shearing of the vertical walls between the terraces. The formation of the shear walls creates the characteristic step-like appearance of the completed lamellar tear. Additional information on the mechanism of lamellar tearing is presented in Appendix A. The factors which contribute to and influence lamellar tearing may be grouped into three categories: design, material and fabrication.

3.3 Design Factors

The susceptibility of a structural component or joint to lamellar tearing is affected by those design factors which determine the internal resistance of the joint and the resulting accumulation of weld metal shrinkage strain in the through-thickness direction. The principal design factors which influence the risk of lamellar tearing are:

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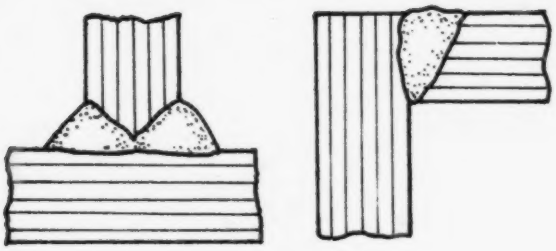
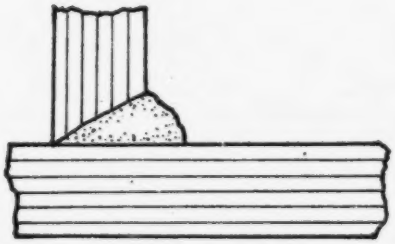
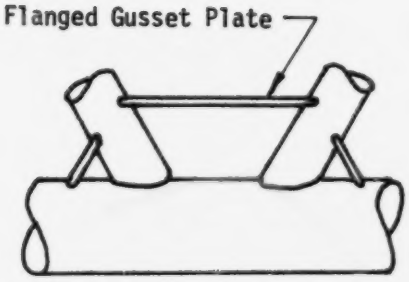


- Weld Orientation. Joint configurations which orient the weld fusion boundary parallel to the direction of rolling of the base metal promote the development of through-thickness strains. Tee (T) and corner joints, the primary examples of such joints, are used extensively in ships and offshore structures.

- Joint Restraint. The level of joint restraint is an important factor in determining the amount and concentration of strain at the connection and is influenced by the size, balance, and distribution of the weld. Welds which are larger than those required to accommodate the design loads unnecessarily increase the weld shrinkage strains as do the unwarranted use of wide groove angles and full penetration welds in place of properly sized fillet welds. In multipass welds, the size of the weld bead determines the number of passes required to fill the joint. The smaller the bead size, the greater the number of required passes and the higher the weld shrinkage strains.



Joint designs with large single-sided welds cause unsymmetric strains to concentrate on the side of the weld. Double-sided welds reduce and balance the shrinkage strains with a resultant decrease in the risk of lamellar tearing.



- Component Restraint. Structural components fabricated of thick and/or curved plates, and stiffened with heavy brackets or gussets have inherently more restraint in the through-thickness direction than components fabricated of unstiffened, thin, flat plates.

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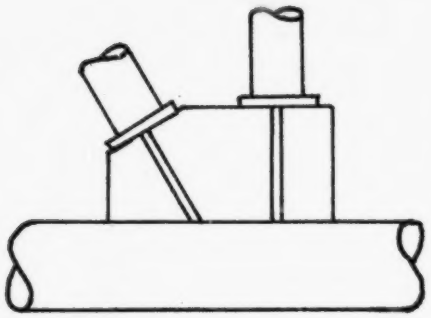

Examples of high component restraint usually can be found at the multi-column connections or node joints of mobile and fixed offshore structures.

- Weld Metal Strength. When the yield point of the weld metal is significantly higher than that of the base metal, all of the weld shrinkage strains must be accommodated by the base metal matrix. The concentration of the strain in the base metal increases the risk of lamellar tearing. Weld metal is usually "matched" to the base metal on the basis of equivalent tensile strengths. However, weld metals which match the tensile strength of the base material generally have significantly higher yield points than the base material.

3.4 Material Factors

A detailed discussion of the metallurgical factors which influence the susceptibility of rolled steel plates to lamellar tearing would be too voluminous to include in a practical guidance manual for designers and engineers. However, an understanding of the fundamental metallurgical considerations is necessary to obtain an appreciation of the complexity of the problem and the underlying rationale for the control methods presented in Section 6. Additional information on the material factors influencing lamellar tearing may be found in Appendix B and the selected works listed in the bibliography.

Lamellar tearing is directionally sensitive and at least partially dependent on the through-thickness properties of the base material. The anisotropy of hot-rolled steel plates usually produces the greatest strength and ductility in the longitudinal and transverse directions with significantly less ductility in the through-thickness direction. The susceptibility of carbon and low-alloy steels to lamellar tearing is primarily dependent on these low through-thickness (Z-direction) ductilities. The type, number, shape and distribution of the nonmetallic inclusions, as well as the matrix properties of the particular grade of steel, are generally considered responsible for the reduction in ductility in the Z-direction.

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All normal quality structural steels for hull and marine applications contain quantities of exogenous and indigenous inclusions. Exogenous inclusions usually consist of ladle refractory, ingot scum, or slag that is occasionally trapped in the ingot during solidification. They are usually large in comparison to indigenous inclusions and when located close to the surface of a rolled plate significantly increase the susceptibility of the plate to lamellar tearing.

Indigenous inclusions are formed as a result of the chemical reaction of elements in the steel or elements added to the steel usually during deoxidation. The number and distribution of indigenous inclusions depends on the steel grade and its chemical composition, the deoxidation procedure, the melting technique, position in the ingot, and the hot working temperature. When the ingot is rolled to form a plate or section the inclusions are progressively elongated and flattened to varying degrees to form plates or stringers parallel to the plate surface. Material which has high concentrations of elongated or flattened inclusions will have lower through-thickness ductility and a greater susceptibility to lamellar tearing.

The dominant inclusions are sulfides and oxides with the deoxidation practice determining the type of each inclusion present. For comparison purposes deoxidation practices are usually classified in two categories: non-aluminum treated and aluminum treated. In semi- or fully-killed non-aluminum treated steels silicates and Type I manganese sulfides are the primary types of inclusions. Type II manganese sulfides and alumina are the principal inclusions in fully-killed aluminum treated steels while Type III manganese sulfides and alumina inclusions predominate in fully-killed with excess aluminum materials. In the non-aluminum treated steels the silicates become more elongated than the sulfides during hot rolling and are primarily responsible for the reduction in Z-direction (ST) ductility. However, in aluminum deoxidized steel the rod shaped manganese sulfide inclusions become highly elongated during rolling and are the primary cause of the low Z-direction ductility. High concentrations or elongated clusters of manganese sulfides and alumina can also produce locally poor Z-direction ductility in non-aluminum and aluminum treated steels, respectively.

Many of the earlier works on metallurgical aspects of lamellar tearing emphasized the importance of sulfur content and inclusion shape control to improve through-thickness ductility as measured by the percentage reduction of area in the short-transverse direction. For a reduction of area higher than 25 percent (a level at which the risk of lamellar tearing is significantly reduced), the sulfur content must be lower than 0.010 percent. Addition of rare-earth (RE) metal reduces the residual sulfur levels while also preventing the formation of manganese sulfides and silicates, forming instead only small globular shaped RE-containing inclusions. However, for non-aluminum treated steels, where silicates are primarily responsible for reducing the Z-direction ductility,

the sulfur content alone can give an inadequate indication of the susceptibility of the material to lamellar tearing. Improved manufacturing processes such as electroslag remelting and calcium-argon-blowing may also be used to reduce the maximum sulfur levels and/or remove most of the nonmetallic inclusions.

The properties of the steel matrix are also important in all phases of tearing. For steels with a low-strength, highly ductile matrix, the material at the edges of inclusions can deform plastically without propagating the fractures or voids formed by the decohesion of the nonmetallic inclusions and the matrix materials. In higher strength steels, the through-thickness ductility decreases while the higher yield strength of the matrix material permits the development of high-strain levels across an inclusion before the matrix yields. These higher strain levels in turn facilitate the extension and joining of adjacent voids in the second phase of tearing.

Ferrite-pearlite banding in the steel matrix has also been reported to cause both initiation and propagation of lamellar tears, partially because the ferrite has a lower cleavage fracture stress than the pearlite. Strain aging, hydrogen embrittlement and differences in the thermal expansion between the inclusions and the steel matrix all contribute in some degree to the susceptibility of steel plates to lamellar tearing. Susceptible steels with high brittle fracture transition temperatures show improved resistance to tearing when preheated above the brittle fracture transition temperature before welding [2].

3.5 Fabrication Factors

Fabrication practices, particularly welding variables, help to determine the level of joint restraint and the resulting risk of lamellar tearing. Factors which affect lamellar tearing susceptibility include preheat temperature, heat input level, bead or run sequence, and fabrication sequence. Increasing preheat and heat input levels are reported to increase the postweld ductility of the metal with a corresponding improvement in tearing resistance. Explanations for the apparently lower risk of tearing with higher preheat and heat input welding processes are varied and include increased weld penetration and weld metal deposition rate, reduced rate of post weld cooling and production of a wider, softer and tougher HAZ. Increased penetration can intercept and blunt existing laminations while higher deposition rates decrease the required number of weld runs and the subsequent number of strain cycles. The reduction in cooling rates permits stress relaxation and the development of smaller strain gradients. The use of higher heat input processes will also produce lower strength welds which will accommodate more of the shrinkage strain. In addition to improving the postweld ductility of the material, preheating may retard the propagation of lamellar tearing by raising the temperature of the susceptible material above its brittle fracture transition temperature.

Based on these research results the influence of higher preheat and heat input welding processes on the incidence of lamellar tearing appears substantial. However, reports of fabricator experience indicate little or no discernible success with increasing preheat or heat input within a given welding process. On the contrary, higher preheat and heat input levels may increase the amount of subcritical tearing and contraction strains.

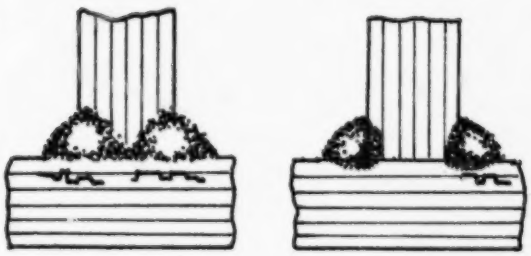
The sequence of depositing the weld beads or runs can significantly affect the level and concentration of shrinkage strains near the HAZ and parallel to the direction of rolling of the base plate. When fabricating double-sided T joints unsymmetrical depositing of the weld metal can cause strains to concentrate on the side of the weld. Symmetrical deposition of the runs will reduce and somewhat balance the weld shrinkage strains.

In multi-joint components the fabrication or welding sequence can affect the restraint level of each joint at the time of welding. The risk of lamellar tearing increases when the more susceptible joints are made towards the end of the fabrication sequence when the maximum restraint of the structure is being approached.

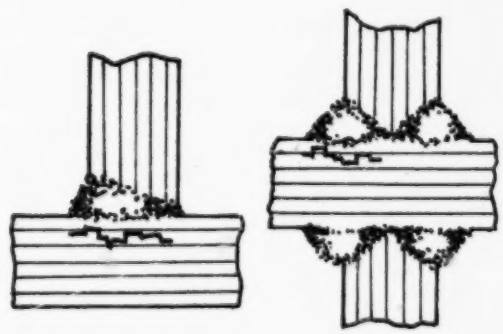
4. OCCURRENCE OF LAMELLAR TEARING

4.1 What Types of Structures Are Susceptible to Lamellar Tearing?

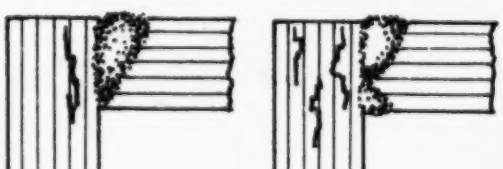
Lamellar tearing usually occurs at highly restrained joints in large welded structures. The restraint may be imposed by a massive component or by a smaller one which has been stiffened. Tee (T) and corner joints are the two basic joint configurations most susceptible to lamellar tearing. The cruciform joint is considered a more severe form of the T joint since the restraint of the base plate in way of the weld is higher. The susceptibility of these joints reflects the fact that the internal restraint of the joint in the through-thickness direction is sufficient to cause the weld shrinkage strains to exceed the ductility limits of the base metal.



With the exception of cruciform joints, T joints with single or double-sided full-penetration welds have the greatest incidence of tearing. T joints with simple fillet or partial penetration rather than full-penetration welds appear to present less risk as do balanced double-sided welds compared to large single-sided welds.



In corner joints, tearing can occur in one or more planes through the base plate thickness. The tears often extend to the exposed plate edge where they are either visible or readily detected by standard non-destructive testing methods such as dye penetration or magnetic particle inspection.



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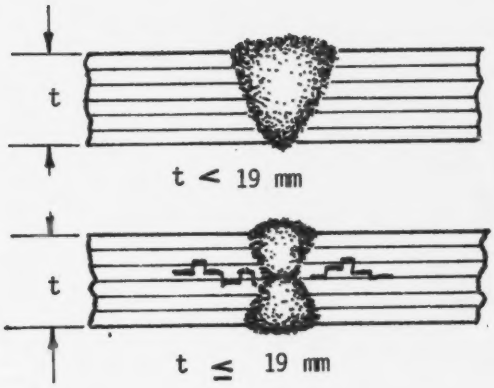
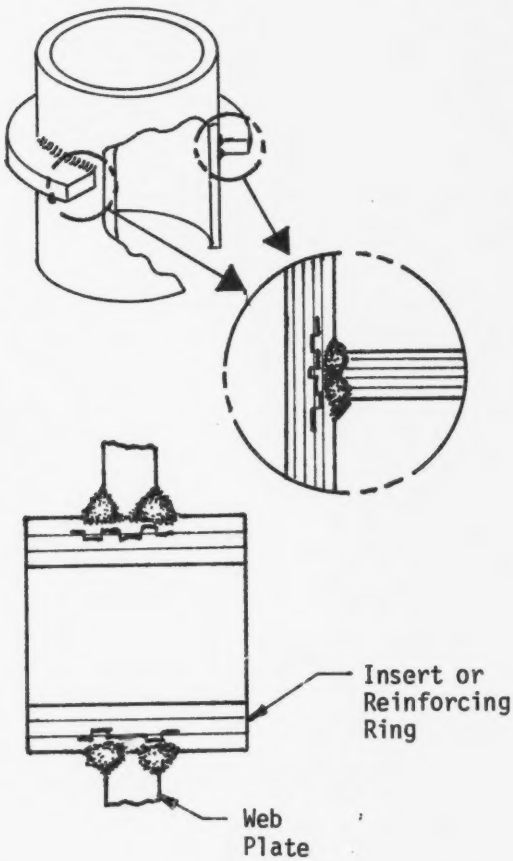


The risk of lamellar tearing in conventional butt joints for plate thicknesses less than 19 mm is negligible, since the weld fusion boundary is at a large angle to the plate surface. However, tearing has been reported in butt welds of thick plates ($t \geq 19$mm) with an x-groove.

In the heavy fabrication and construction industries, lamellar tearing is commonly reported to occur in the following types of structures:



- Nozzle or insert set through a rigid plate. Tearing can occur in a rolled plate nozzle or penetrator set through a vessel shell plate or end wall, or in a fabricated insert in the web of a large girder. For example, a Vierendeel girder fabricated of heavy plate sections with a ring stiffener set into the web opening is susceptible to lamellar tearing in the ring stiffener. In all cases, any tearing will occur only in the nozzle or insert plate.

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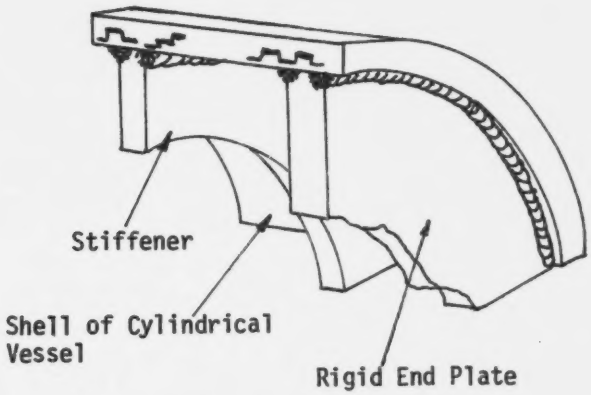
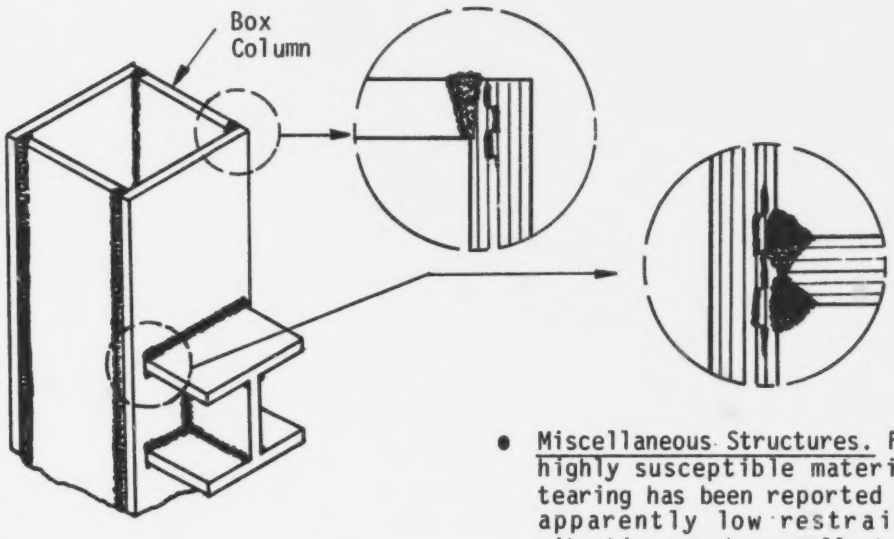
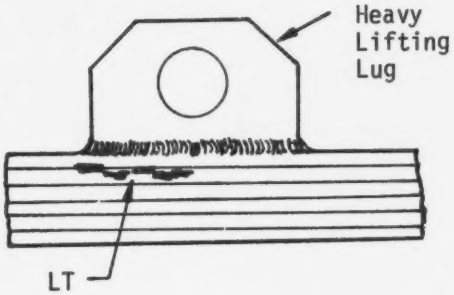


Stiffeners or end closure plates in cylindrical structures. Shell plates of cylindrical structures which are in way of the end closure plates or heavy internal stiffeners are susceptible to lamellar tearing. In structures of this type the tears can be completely subsurface and difficult to detect.

- Box structures and stiffened joints such as beam-to-column. Structures in this category range from simple box columns to large structural configurations with complex multi-member connections.





- Miscellaneous Structures. For highly susceptible material, tearing has been reported in apparently low restraint situations such as pullout of lifting lugs and in flange-to-web connections in fabricated I-beams. The risk of lamellar tearing in apparently simple, unrestrained joints makes it essential that for critical components, such as lifting lugs, post weld inspection for tearing be performed and often accompanied by a reduction in the through-thickness service loads.

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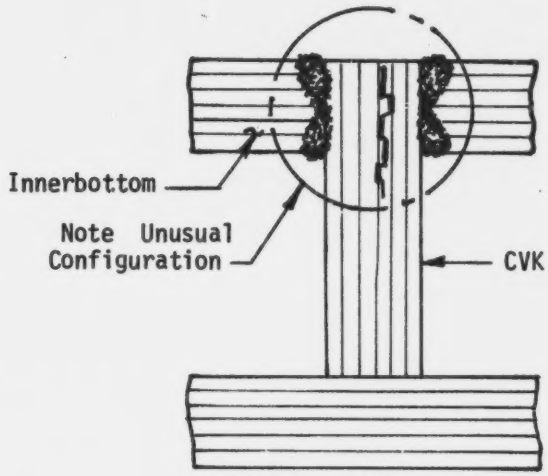
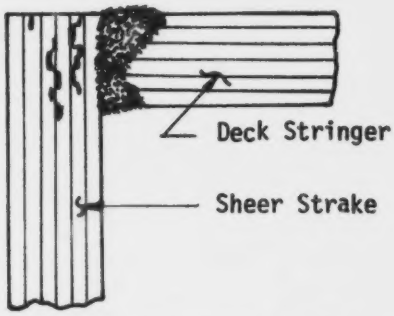
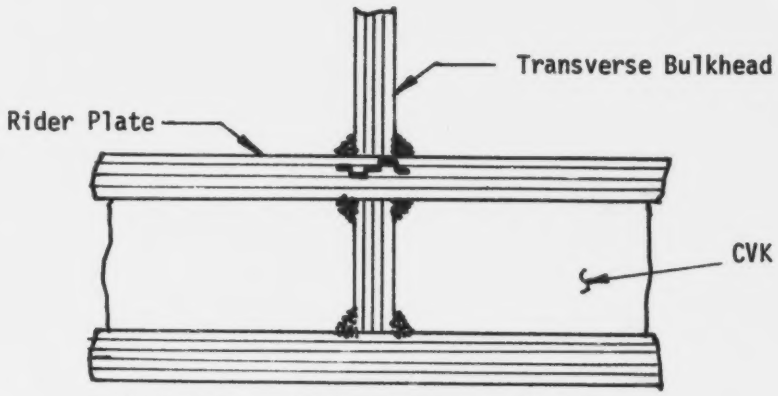
Documented cases of lamellar tearing are extremely rare for ships under construction or in service. However, isolated instances of lamellar tearing have been reported in the following types of structural connections: CVK/innerbottom, CVK rider plate/transverse bulkhead, deck stringer plate/side shell sheer strake, container buttress supports and thick-walled box girders of large container ships.



CVK/Innerbottom



Deck Stringer/Sheer Strake



CVK Rider Plate/Transverse Bulkhead

Bulkhead or innerbottom heel connections, heavy stern frame weldments and thick web frame flange to longitudinal bulkhead connections in large tankers are also considered susceptible to lamellar tearing, although no actual failures have been reported.

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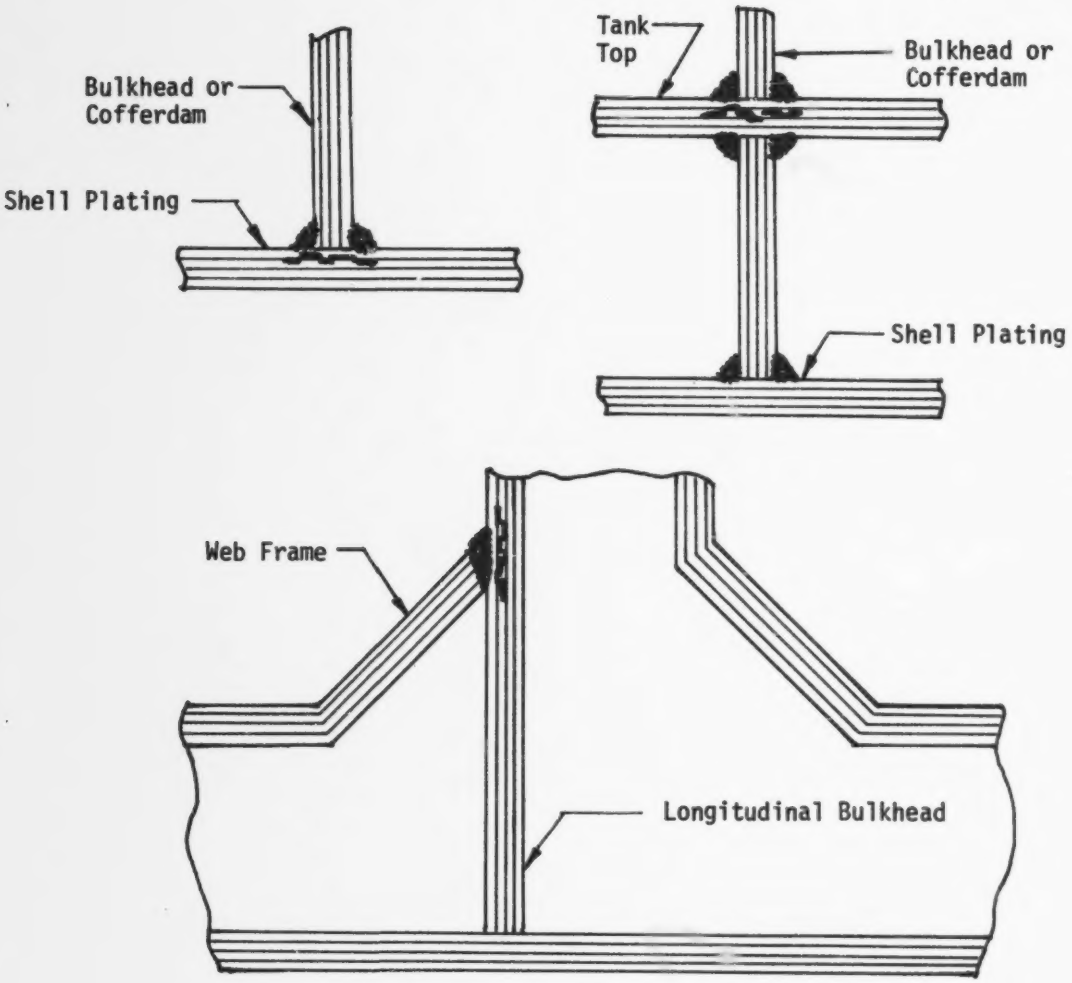

It is important to note that all of these susceptible ship details are essentially variations of the basic corner, T and cruciform joints described in the beginning of this section as being the most susceptible to lamellar tearing. The welds may be either of the double continuous fillet or bevel groove type with full or partial penetration.

To date, lamellar tearing has not been responsible for either numerous or critical failures in shipbuilding. While it cannot be considered a serious problem based on the rate of occurrence, the designer or engineer must be aware that lamellar tearing can be a potentially significant problem when it occurs in critical connections, such as bulkhead or cofferdam heels. In these areas, procedures for the control, detection and, if necessary, the repair of lamellar tears should be implemented. Where the increase in the size of ships results in structural assemblies fabricated from thicker plates, the risk of lamellar tearing in joints which are

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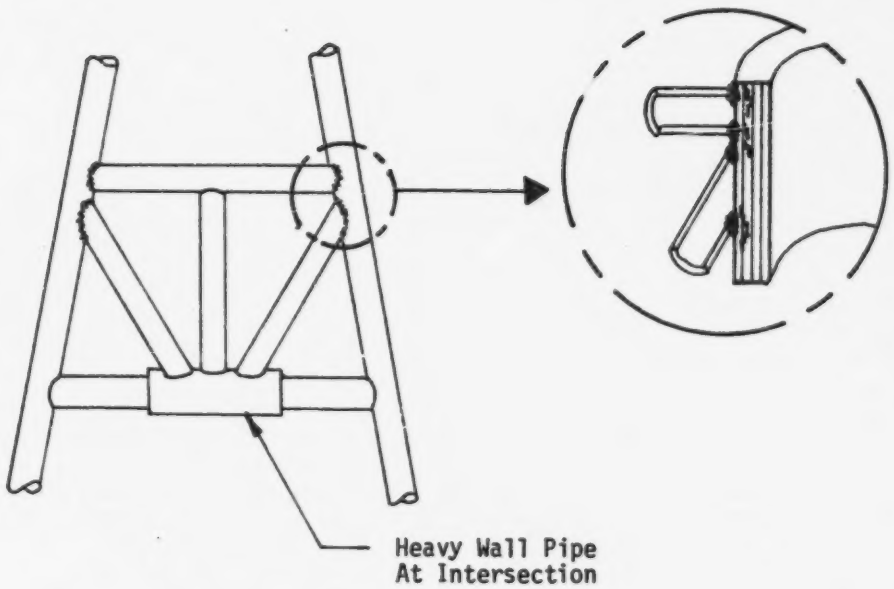
acceptable when fabricated of thinner material should be re-evaluated. While the significance of lamellar tearing should not be underestimated, the extent of the problem should not be exaggerated to the point that expensive materials, and fabrication and inspection procedures are unnecessarily specified.

The problems of lamellar tearing in marine structures are considerably more significant in the construction of mobile and fixed offshore drilling platforms. The configuration of these structures is very complex with the use of thick plates in highly stressed welded T and cruciform joints. These joints usually take the form of multi-column connections or node joints at which tubes of large diameter and thick section pass through or are surface welded to another tube with full-penetration fillet welds.



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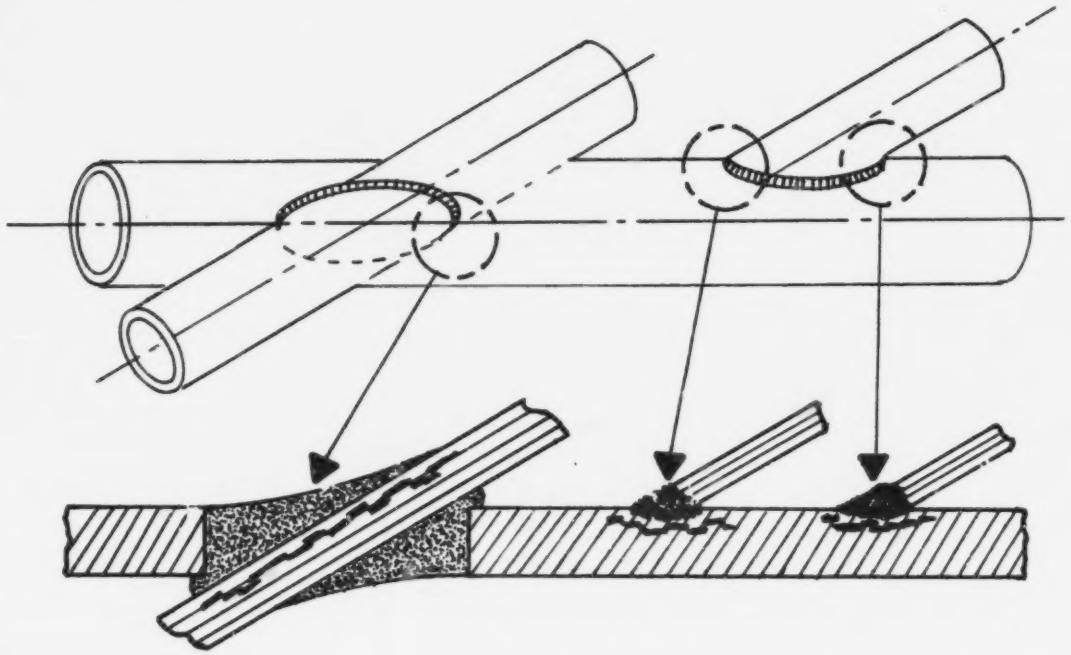

Sample structural connections of column stabilized and self-elevating mobile offshore units and fixed jacket type platforms which are susceptible to lamellar tearing include:

Column Stabilized Units

1. Intersection of vertical columns and upper and lower hulls.

2. Major intersections of horizontal and vertical braces with themselves and with the vertical column.

3. Portions of deck plating, heavy flanges, and bulkheads within the upper hull or platform which form box or I type supporting structure.

Self-Elevating Units

1. Jack house supporting structure and bottom footing structure.

2. Vertical columns in way of the intersection with the mat structure.

3. Combinations of deck, side, bottom and bulkhead plating within the upper hull which form box or I type supporting structure.

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Jacket Type Fixed Platforms

1. Deck to leg can intersections.

2. Major intersections of horizontal and vertical braces with themselves and with the vertical can columns.

4.2 How Often Does Lamellar Tearing Occur?

Lamellar tearing has been estimated to occur in significantly less than one percent of all weldments. The frequency of occurrence increases slightly for large welded structures fabricated of plates or sections over 25 to 30 mm in thickness under conditions of high restraint in the through-thickness direction. For applications which do not satisfy the essential conditions of material susceptibility and through-thickness strains due to welding procedures and joint configuration, the risk of lamellar tearing is negligible.

The frequency of lamellar tearing in the construction of ships, and mobile and fixed offshore structures is difficult to estimate. Replies to questionnaires sent to the world's major classification societies indicate that the incidence of lamellar tearing in shipbuilding is small. Isolated cases of lamellar tearing in such connections as the deck stringer plate/side shell sheer strake have been virtually eliminated by the use of improved weld and joint details.

The problem of lamellar tearing is considerably more serious in the construction of mobile and fixed offshore drilling platforms. The greater susceptibility to tearing of the large number of highly restrained T and cruciform joints in these structures increases the frequency with which lamellar tearing occurs when normal structural quality steel (sulfur content $>$ 0.020% by weight) is used. The frequency of tearing is reduced significantly when steels with improved through-thickness properties are used in conjunction with revised welding procedures and joint designs. One oil company which fabricates 15 to 20 fixed offshore structures a year estimates their frequency of lamellar tearing at less than one per year.

4.3 When Does Lamellar Tearing Occur?

Lamellar tearing usually occurs during fabrication, often at an advanced stage where the maximum level of restraint is approached. There is considerable disagreement in the literature concerning the time and temperature at the onset of tearing. Some reports indicate that lamellar tearing is initiated shortly after additional weld metal is deposited over previous beads which have cooled to the point of developing weld shrinkage strains sufficient to cause decohesion at the interface between microscopic nonmetallic inclusions and the surrounding matrix. Other reports conclude, however, that tearing is an ambient temperature, delayed cold-cracking phenomenon.

4.4 What Types of Steel Are Susceptible To Lamellar Tearing?

Lamellar tearing has been encountered primarily in normal quality structural steel plates of the carbon, carbon-manganese and low-alloy types. The steel may be in the normalized, as-rolled, controlled-rolled or quenched and tempered condition, or be fine or coarse grain. Examples of typical American Society for Testing and Materials (ASTM) and American Bureau of Shipping steel specifications with reported histories of lamellar tearing include [3]:

Specification	Type of Product
ABS AH36	Higher Strength Hull Structural Steel
ASTM A36	Structural Carbon Steel
ASTM A283	Structural Carbon Steel - Low and Intermediate Tensile Strength
ASTM A285	Pressue Vessel Carbon Steel - Low and Intermediate Tensile Strength
ASTM A515	Pressure Vessel Carbon Steel - For Intermediate and Higher Temperatures
ASTM A516	Pressure Vessel Carbon Steel - For Moderate and Lower Temperatures

Nonmetallic inclusions have been shown to be primarily responsible for low through-thickness ductility and the void initiation phase of lamellar tearing; and the deoxidation method used in the steelmaking process determines the types of inclusions present in the steel. The earlier literature indicated that aluminum treated-semikilled steels could be expected to have better resistance to lamellar tearing than silicon-treated semikilled steels. However, recent studies report that the lamellar tearing mechanism is too complex to simply relate susceptibility to steel grade or inclusion type. Hence, aluminum treated or semikilled steels cannot be considered more or less susceptible to tearing than non-aluminum treated or fully killed steels.

In theory, there is an increased risk of lamellar tearing with increasing strength levels. For higher strength steel, the through-thickness ductility decreases while the greater strength properties of the steel's matrix material will permit the development of higher elastic strain across an inclusion before the matrix itself yields. The increased susceptibility of higher strength steels is offset in some cases by the increased flexure during welding due to the use of the smaller thicknesses permitted by the higher strength. Some higher quality, high-strength alloy steels, such as HY-80, HY-100, HY-130 and HY-180, have shown minimum susceptibility to decohesion cracking. However, this result is attributed to the increased cleanliness (reduced inclusion content) of these special-purpose steels produced by electric furnace steelmaking, coupled with vacuum degassing.

Lamellar tearing occurs primarily in rolled structural plates, to a lesser degree in rolled sections and rarely in forgings. Steel castings are not susceptible to tearing.

4.5 What Steel Thicknesses Are Susceptible To Lamellar Tearing?

Lamellar tearing has occurred in plates ranging in thickness from 10 to 200 mm, with the most common incidence being in plates 25 to 60 mm thick. Thin plates usually have lower ductility in the through-thicknesss direction than thicker plates due to the greater deformation of inclusions in thin plates during rolling. However, they do not necessarily exhibit a greater incidence of tearing, since flexure of the thinner plates tends to limit the strains in the through-thickness direction. Exceptions to this generalization are rolled plate nozzles, cruciform joints and highly stiffened structural configurations which limit the flexure of the thinner plates.

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5. SIGNIFICANCE OF LAMELLAR TEARING

Where detected, lamellar tearing can result in costly repairs and fabrication delays. The significance of undetected or unrepaired tears on the service performance of the structure varies with the type of loading. The following sections evaluate the effects of lamellar tearing on the static, dynamic and fatigue modes of loading.

5.1 Static Load Condition

The extremely few reported incidences of lamellar tearing failures in service indicates that the strains developed during welding are more likely to cause tearing than the static design or service loads. Localized strains as high as 2% have been reported during welding and the immediate post welding cool-down period. By comparison, the offset strain level, corresponding to the yield point of most structural steels, is only 0.2%. Since design stresses are always significantly lower than the yield stress of the material, the strains encountered in service are at most only 10% of the strains developed during welding. Preliminary results of research done in the United Kingdom at The Welding Institute indicate that even in cases where extensive tearing is initially present through-thickness static stress levels greater than the yield strength of the base metal are required to extend the tears to complete failure. However, as the extent of the initial tearing increases, the stress levels necessary to promote failure decrease [3].

Lamellar tearing is reported to have no effect on the service performance of joints stressed primarily in compression in the through-thickness direction. In joints subject to shear, the service performance will not be diminished provided there is sufficient area in the remaining ligaments between the tears. In areas of extensive tearing, the maximum shear-load capacity of the joints may be reduced.

5.2 Dynamic Load Condition

Very little information is found in the literature concerning the effect of lamellar tearing on the ability of a structure to withstand dynamic loads. A few studies report reduced Charpy V-notch impact energies and dynamic tearing properties in the through-thickness direction. Shock tests performed by the British Navy on full-penetration welded T-joints, fabricated of HY 80 and two grades of C-Mn and low alloy steels, showed that lamellar tearing could be initiated by dynamic loads. Of the three steels tested, only the HY 80, with its greater Z-direction ductility, failed to develop lamellar tears. Although not conclusive, these reports would seem to indicate that materials with lower Z-direction properties are more susceptible to lamellar tearing when exposed to dynamic loads. Conversely, the presence of undetected tears can only increase the risk of failure during dynamic loading.

5.3 Fatigue

For low cycle fatigue, existing lamellar tears will gradually extend and may ultimately result in complete failure as the number of cycles approaches the design limit [1]. However, in practice, catastrophic failure may be avoided by the transfer of load to other members of the structure. Stress concentrations at the root or toe of the weld may be more detrimental than existing tears or poor Z-direction ductility when the structure is exposed to high-cycle fatigue (greater than 10^6 cycles) [3].

6. CONTROL OF LAMELLAR TEARING

Since design, material and fabrication factors contribute to lamellar tearing, control of tearing must address these same parameters. It is evident from Sections 2 and 3 that the causes of lamellar tearing are applicable to generic types of weldments which are independent of the specific end product. It matters little whether the susceptible weldments are in a skyscraper, nuclear power plant, super tanker, or large offshore structure. Accordingly, most of the following recommendations for the control of lamellar tearing in the marine industry are presented in their most fundamental form. It is imperative that the naval architect or designer use judgement to arrive at the optimum balance of joint design, material selection and cost effective fabrication procedures suitable for the application.

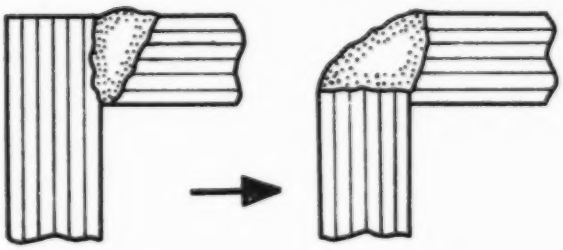
6.1 Joint Design

The avoidance and control of lamellar tearing must begin at the design stage. The design of susceptible joints such as those shown in Section 4 should be optimized where practicable to:

- Avoid excessive through-thickness strains
- Reduce joint restraint
- Reduce component restraint
- Allow for the use of low-strength weld metals

6.1.1 Avoidance of Excessive Through-Thickness Strains

Methods for avoiding the creation of weld shrinkage strains in the through-thickness direction include:



Susceptible Improved

- Welding between the ends of plates rather than on the surface of the susceptible material. This welding technique directs the shrinkage strains in the X or Y directions rather than in the critical Z direction and may require the use of electroslag welding.

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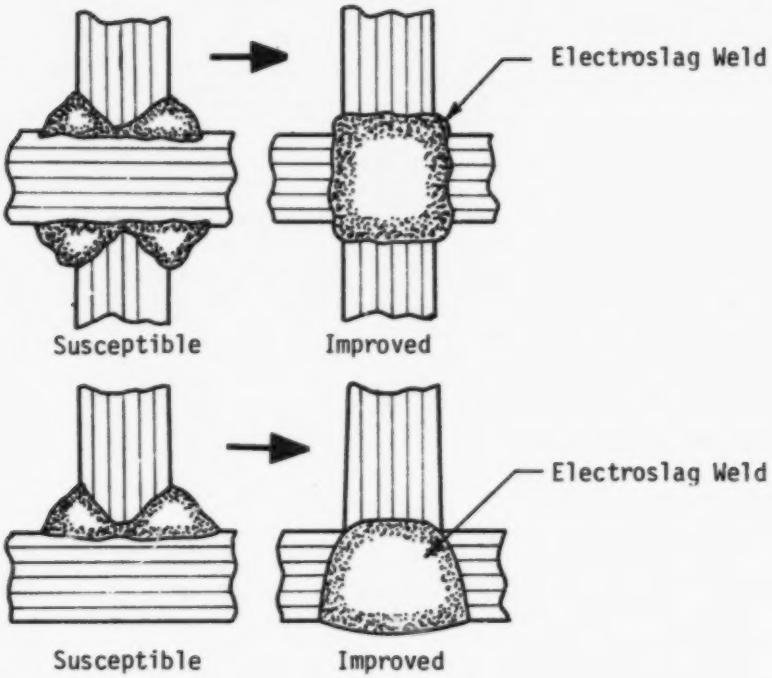

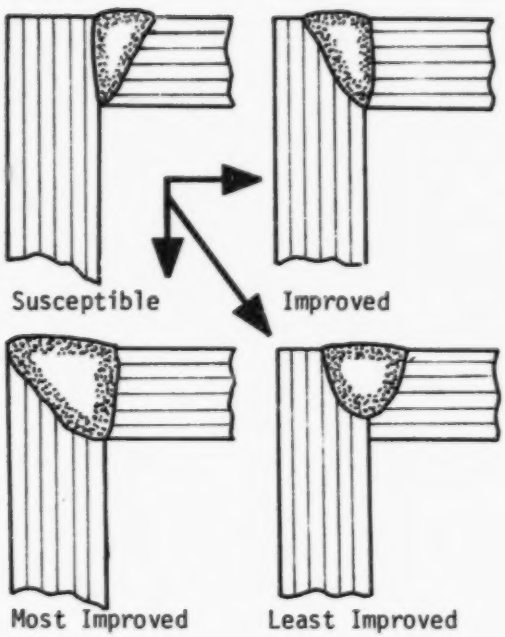

- Orienting the weld fusion boundary at an angle to the surface of the susceptible plate. Large bevel angles offer less risk of tearing, but the edge preparation cost and the volume of weld metal required is also higher than for smaller edge angles. Selection of a cost-effective angle must consider the susceptibility of the plate, the importance of the connection and the relative cost of fabrication.

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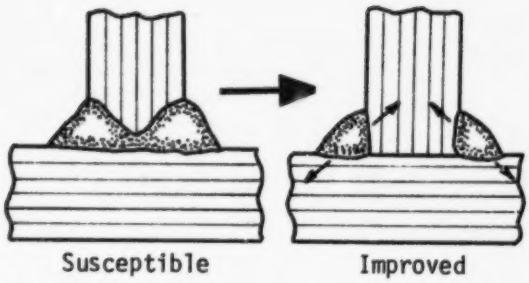
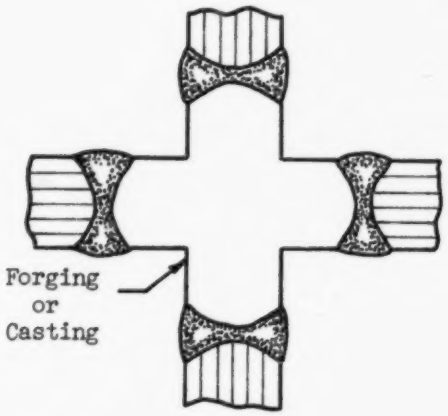


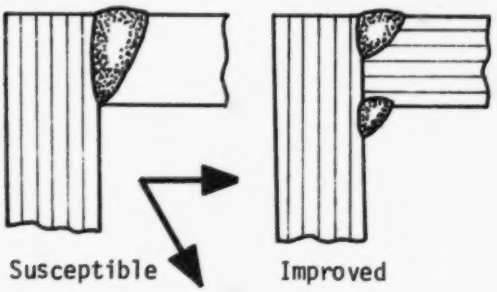
- Replacing of double-sided, full-penetration welds with symmetrical fillet or partial-penetration welds to minimize the volume of weld material and reduce the strain in the Z-direction. The total shrinkage of the fillet welds occurs at an oblique angle to the plate surface thereby further reducing the strain component in the Z-direction.



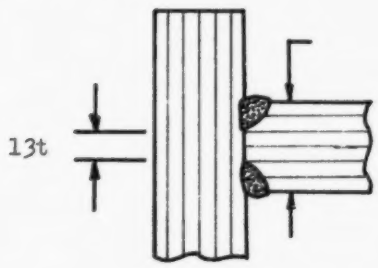
- Using castings or forgings in some critical T and cruciform joints to eliminate the critical welds and any risk of lamellar tearing. This method is expensive, involves considerably more welding, and is generally used in highly critical situations in pressure vessels.

6.1.2 Reduction of Joint Restraint

Methods of reducing joint restraint include:



- Reducing the size of the weld by not using welds larger than necessary to transfer the calculated design loads. For example, full-penetration welds at the deck stringer plate/sheer strake connection can often be replaced by smaller partial penetration or fillet welds.



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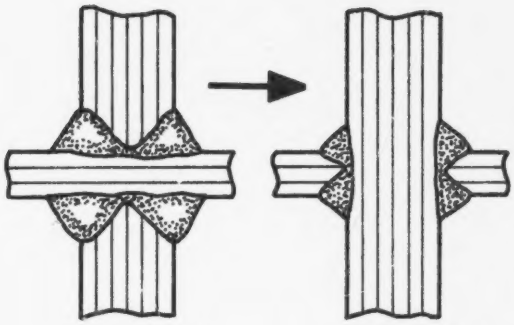
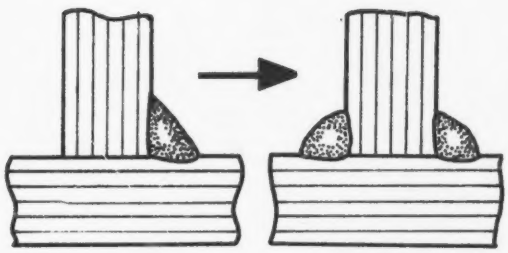
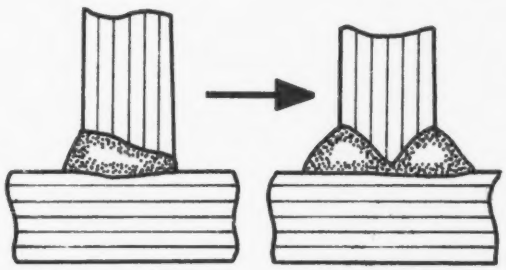


- Joining plates of different thicknesses so that the weld size may be reduced by placing it in the thinner plate.





- Replacing large single-sided welds with balanced double-sided welds in order to eliminate the unsymmetric concentration of strain.

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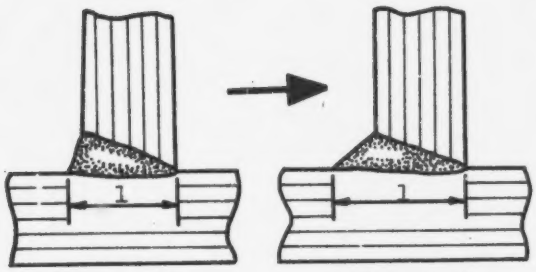

Susceptible Improved

- Selecting weld configurations which distribute the weld metal over more of the surface of the susceptible plate. The use of smaller weld sizes of longer length or double fillets in place of full penetration welds reduces the volume of weld metal and diffuses the shrinkage strains over a larger area of the susceptible plate.

- Other methods include specifying low yield strength weld consumables and the use of buttering. These methods are discussed in other sections.

6.1.3 Reduction of Component Restraint

Component restraint can sometimes be reduced by modifying the structural configuration or scantlings. Methods of decreasing the level of restraint include:

- Avoid complex, multi-member connections. This prohibition is not always practical in structures such as fixed and mobile offshore drilling units.

- Minimize member stiffness by using scantlings of minimum thickness.

- Use flat plates instead of curved members wherever possible.

- Do not use stiffeners, brackets or gussets not specifically required by the design calculations. Scantlings and welding of all auxiliary stiffening should be the smallest required to suit the design loads.

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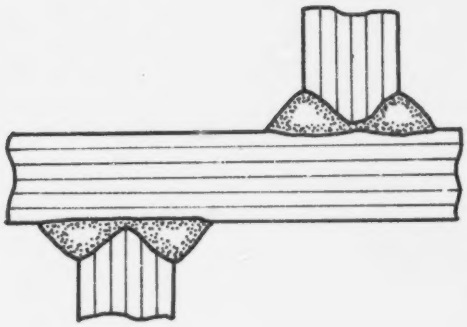
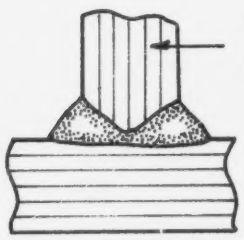


- In cruciform joints stagger the members on opposite sides of the susceptible plate. This method is not always desirable in highly loaded joints.



- If possible, use lower strength material for the member causing the strain in the through-thickness direction.

6.1.4 Selection of Weld Material

To accommodate more of the weld shrinkage strain in the weld metal select, where possible, welding consumables which match the yield strength rather than the tensile strength of the susceptible base plate. Detail calculations of the stresses across the joint will usually have to be prepared to justify the use of lower tensile strength consumables. Low-hydrogen consumables are recommended in order to avoid embrittlement of the heat-affected zone.

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6.2 Material Selection

6.2.1 Grade of Steel

Inquiries made to the major ship classification societies indicate that the most successful and cost-effective method of preventing lamellar tearing is the use of steels with improved through-thickness (Z-direction) properties at susceptible connections. Improved Z-grade steels have been used primarily in the construction of fixed and mobile offshore structures. The limited use to date of the Z-grade materials in shipbuilding reflects the limited occurrence of lamellar tearing in the construction of conventional ships and the fact that many of the susceptible connections (such as the gunwale) have been easily corrected by modifying the joint configuration and welding procedures. However, Bureau Veritas has reported that two shipyards have put strakes of special Z-grade plates in the tank top of LNG ships [4]. These plates are used at the critical intersections of the heels of cofferdams which form the secondary containment boundary for the liquefied gas.

Specifications for steels to be used in critical components of offshore structures have, in the past, specified maximum sulfur content, minimum Z-direction tensile strength, minimum Z-direction percentage elongation and reduction in area (RAz), and maximum allowable inclusion content. However, high yield and ultimate tensile-strength values in the Z-direction do not necessarily reduce the risk of lamellar tearing. The percentage elongation measured by conventional tensile-test procedures also does not provide a reliable measure of tearing susceptiblity, since it may include deviations caused by the formation of small fissures adjacent to nonmetallic inclusions. Furthermore, the small gauge length of samples taken from thin plates makes it very difficult to measure elongation in the Z-direction with any acceptable degree of accuracy. While sulfur content can give an indication of the susceptibility of aluminum deoxidized steels, it is not applicable to non-aluminum treated steels where silicates are primarily responsible for reducing the Z-direction ductility. The measure of inclusion content by the prefabrication ultrasonic inspection of the steel plates has by itself been inadequate for assessing the risk of lamellar tearing.

At present, the percentage reduction in area in the Z-direction (RAz) is the most practical and accurate measure of material susceptibility. Reports published by the Welding Institute show good correlation between measured RAz and observed incidences of lamellar tearing [5]. RAz is being increasingly used by the major ship classification societies to define and approve Z-grade steels for use in ships and offshore structures. These requirements define

up to three Z grade plate categories which vary according to their minimum guaranteed mean value and the minimum individual value of RAz. The following example from Bureau Veritas' rules for offshore platforms is typical [6]:

Grade Category	Minimum Guaranteed RAz, Mean Value *	Minimum Individual RAz Value
Z15	15%	10%
Z25	25%	15%
Z35	35%	25%

* Mean obtained from three tests.

Due to the complex interrelationships between the factors which can cause and control lamellar tearing, the selection of candidate sites and Z grade category is usually left to the discretion of the designer subject to the classification society's approval during design review.

When selecting materials for susceptible components in offshore structures the following requirements should be observed:

- At joints connecting structural elements which are essential to the integrity of the structure, and which are subject to high stresses in the through-thickness direction, specify steels with a minimum guaranteed mean value RAz of 25% and a minimum individual RAz value of 15%. Examples of susceptible connections in mobile and fixed offshore structures were noted in Section 4.1. It is noted that some marine classification societies and major oil companies require minimum mean RAz values of 30% to 35% for critical applications such as the node plates in offshore drilling rigs.

- For aluminum treated steels, the sulfur content should not exceed 0.01% by weight.

- Prefabrication ultrasonic inspection of the steel plates to be used in susceptible connections will not give an adequate indication of the materials resistance or susceptibility to lamellar tearing. Where ultrasonic inspection is to be used to indicate the number and size of laminations or inclusions, the plate should be continuously tested along the lines of a mesh grid 100 mm square. All edges should be inspected for a width equal to 1-1/2 times the plate thickness or 100 mm, whichever is greater.

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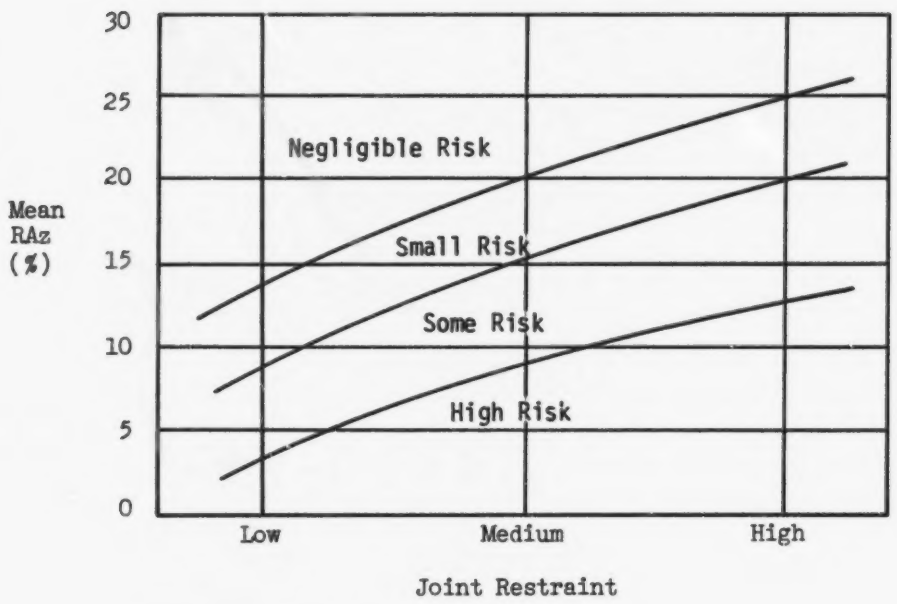
- The following figure, published by the Australian Welding Research Association [1], may be used as a general guide in selecting minimum RAz values for material to be used in structural elements susceptible to lamellar tearing. The designer may vary the required minimum mean RAz value with the importance of the component to the overall integrity of the structure and the level of restraint of the connection. For example, material used in the highly restrained nodes connecting critical members of an offshore drilling rig should have a minimum mean RAz value of 25%. The risk categories shown on the figure are based on a qualitative evaluation of the recommendations of both industrial and marine references (see Appendix B) rather than a statistical forecast of the probability of a lamellar tear occurring. Similarly, the levels of joint restraint cannot be equated with an accepted quantitative measure of restraint. The figure is applicable to steels with a minimum yield stress of 40.8 kg/mm^2 (58,000 PSI) or less. The mean RAz values correspond to those obtained using 6.4 mm diameter test specimens. As noted in Appendix B, the diameter of the test specimen is significant when quoting RAz values.



With the use of electroslag remelting or calcium-argon-blowing steel manufacturing processes, essentially all grades of hull steel used in ships and offshore structures can be purchased with improved Z-direction properties. Typically, electroslag remelting

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will double the price per pound of an ABS AH 32 grade steel. The cost of manufacturing the same grade by the calcium-argon-blowing process is considerably less expensive, adding only approximately 3 cents to the per pound cost of the basic grade. However, calcium processed steels can only obtain a minimum RAz of 25 percent, while steels produced by ESR can obtain minimum RAz values of 30 percent or more. Since the improved Z-grade steels are only used locally at susceptible joints, the total extra cost per structure for the improved materials is often less than the cost of a single repair and the associated construction delays.

6.2.2 Product Type

Where practical, replacing rolled steel plates with other less susceptible types of steel products, such as castings and forgings, will decrease the risk of lamellar tearing.

6.3 Fabrication

6.3.1 Layout and Forming of Susceptible Components

When fabricating components out of plates susceptible to lamellar tearing the following practices can be used to reduce the risk of tearing:

- Plate Position - avoid making heavy attachment welds at the center of the plate width, the extreme edges of plate with as-rolled or uninspected flame cut edges, and areas of the plate where ultrasonic inspection indicates heavy concentrations of inclusions. Caution at the edges of plates is warranted by the fact that the material at an as-rolled edge usually has less through-thickness ductility than the rest of the plate. The heat effects of a cutting torch can result in the decohesion of inclusions in the steel matrix.

- Direction of Rolling - components with high risk of lamellar tearing, such as heavy lifting eyes attached to thick plates, should be oriented with the weld axis at right angles to the primary rolling direction of the susceptible plate.

- Plate Forming - thick cold-formed plates are more susceptible to lamellar tearing and, where practical, should not be used in components requiring large welds.

6.3.2 Welding Process

With the exception of electroslag welding most conventional welding processes are susceptible to lamellar tearing. The frequency of occurrence in processes which utilize higher heat input is less than those whch have a relatively low-heat input. This is most likely due to the deeper penetration, reduced hardness in the HAZ, and the smaller strain gradients encountered with higher heat input. Recommended welding processes in order of decreasing preference (or increasing susceptibility to tearing) are:

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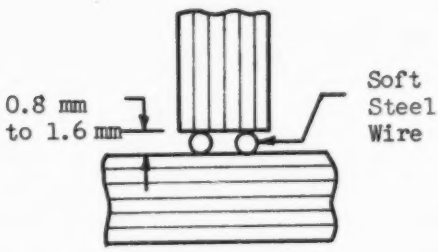
- Electroslag
- Submerged-arc
- Gas shielded metal-arc (MIG or CO_2) and flux-cored arc welding
- Manual metal-arc - low hydrogen electrodes
- Manual metal-arc - non-low hydrogen electrodes

6.3.3 Joint Preparation, Fit-up and Jigging

Other than the requirements conforming to normal good practice, joint preparations to control lamellar tearing should reflect the improved joint designs discussed in Section 6.1. Mainly the joint preparation should provide for a balanced weld with a fusion boundary which is not parallel to the surface of the susceptible plate. Wide groove angles which increase distortion and strain should be avoided and the depth of the weld should be limited to that necessary for the required weld throat thickness. Fillet welds or partial penetration welds should be given preference over full penetration welds.



Tight fit-up and heavy jigs which inhibit lateral weld shrinkage should be avoided. The use of an undressed flame-cut surface or soft-steel wire spacers will permit contraction of the weld metal without producing high concentrations of strain. Copper wire should not be used because it may contaminate the weld metal. Large gaps which increase the volume of weld metal should also be avoided.

6.3.4 Welding Conditions

6.3.4.1 Preheat

As noted in Section 3.5, the use of preheating to control lamellar tearing can be both beneficial and harmful. However, where susceptible joints are preheated either to control lamellar tearing or to satisfy other welding requirements, such as the prevention of hydrogen cracking, the following considerations should be observed:

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- Avoid the creation of additional or concentrated contraction strains by heating all components around the joint for an equal distance and to approximately the same temperature.

- A preheat temperature of approximately 100°C or greater is considered the most effective.

6.3.4.2 Deposition Rate

Welding processes with high weld-metal deposition rates are preferred. The higher deposition rates decrease the number of weld runs necessary to complete the weld with a corresponding decrease in the number of strain cycles. Since deposition rates are primarily a function of the heat input of the welding process, the list and ranking of preferred welding processes are the same as presented in Section 6.3.2.

6.3.4.3 Interpass Temperature

Maintaining proper interpass temperature is necessary to prevent excessive cooling of previously deposited weld metal between runs. Repeated heating and cooling cycles may unnecessarily increase the total shrinkage strains. Recommended practices include:

- Do not permit the interpass temperature to go below the preheat temperature until all welding on the joint is completed.

- As in normal welding procedures, avoid very high interpass temperatures which may unfavorably alter the properties of the steel.

- Allow completed joints to cool slowly and evenly in order to prevent excessive thermal strains.

6.3.4.4 Weld Size and Shape

To decrease the risk of lamellar tearing in susceptible joints the following considerations of weld size and shape should be implemented:

- Use the minimum weld size compatible with the design loads and stress distributions across the joint. Often excessive weld sizes are chosen arbitrarily when the strength requirements across the joint are unknown.

- Welds with deep penetration and uneven shape permit the diffusion of the contraction strains into more of the susceptible material and avoid concentrations.

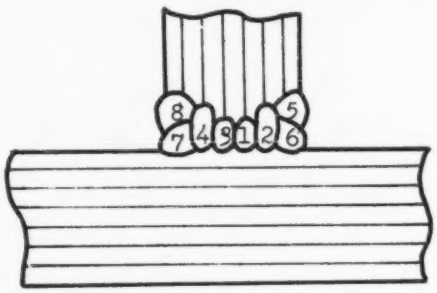
- Increasing the length of the leg on the base plate will also distribute the strains over more of the base metal.

6.3.5 Welding Techniques

6.3.5.1 Run Sequence

Proper sequencing of weld runs will help to reduce the level and concentration of the weld shrinkage strains. Applicable methods include:

- Minimize the number of weld runs in order to reduce the number of heat cycles.
- Deposit a layer of weld metal on the surface of the susceptible plate prior to making connecting runs between the components. These initial runs should be done in accordance with the recommended procedures for buttering and in situ buttering in Sections 6.3.5.2 and 6.3.5.3, respectively.



- Strain concentrations in symmetrically configured T joints can be reduced by depositing weld runs in an alternating, balanced sequence.

6.3.5.2 Buttering

Buttering consists of depositing one or more layers of low yield strength weld metal directly on the surface or in a gouged-out area of the susceptible plate. The purpose of the buttered layer(s) is to accommodate the weld shrinkage strains by spreading them more uniformly through the lower strength weld metal. Buttering also displaces the heat-affected zone away from the susceptible parent metal. In general, buttering has been very successful in preventing lamellar tearing in new weldments and in the repair of existing tears. Points to consider when using the buttering technique include:

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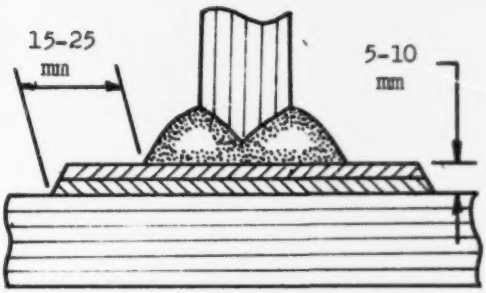
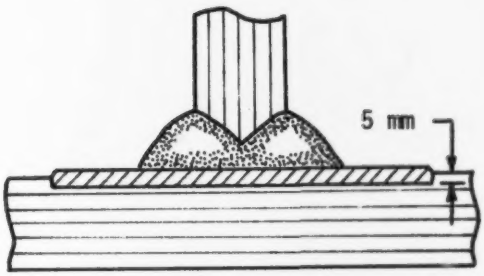


- The buttered layer(s) should be 5 to 10 mm thick and extend 15 to 25 mm beyond each weld toe.



- When the buttered layer is to be applied in a groove, the groove should be approximately 5 mm deep and extend under the full width of the buttering.
- Where buttering is to be used in place of steel with improved through-thickness properties, the relative costs should be thoroughly evaluated prior to fabrication.
- The yield strength of the weld metal should be less than the strength of the base plate.
- Submerged arc welding with low-hydrogen consumables should be used whenever possible to obtain good penetration of the buttering layer(s) and to avoid the buildup of hydrogen in the weld. The level of heat input should also be carefully regulated.

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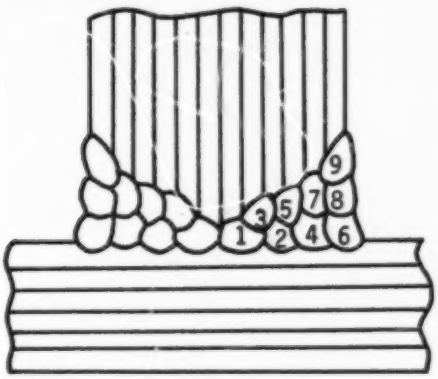
6.3.5.3 In Situ Buttering



This technique is a modification to the run sequence rather than an additional preweld preparation as is conventional buttering. In in situ buttering the first weld runs are deposited on the base plate prior to completing the connecting runs. This method has proven successful in diffusing the weld shrinkage strains at a negligible increase in fabrication cost.

6.3.5.4 Peening

Peening, the controlled working of the weld beads by means of light impact blows to the weld surface to reduce residual tensile stress, has not proven successful in controlling lamellar tearing. Excessive peening can cause loss of toughness and cracking in the weld metal. Although not a viable method of reducing the risk of lamellar tearing, peening in general does not increase the risk of tearing in susceptible material. If employed, the first and closing runs should not be peened. One report indicates that peening of the last weld run may contribute to lamellar tearing [1].

6.3.5.5 Welding and Fabrication Sequence

The restraint level of a welded joint is greatly influenced by the sequence in which the welds in the joint are made and by the fabrication sequence of adjacent components. The following factors should be considered when preparing fabrication and welding schedules:

- In multi-joint components, the more susceptible joints should be made first.
- Completely weld subassemblies prior to final assembly to limit the number of critical joints.
- Minimize strain accumulation by welding from area of maximum restraint to free edges or other areas of minimum restraint.
- For individual joints, sequence the welding so that the level of restraint will be minimized for the largest welds.
- Minimize the size and number of tack welds used to hold components together during welding.

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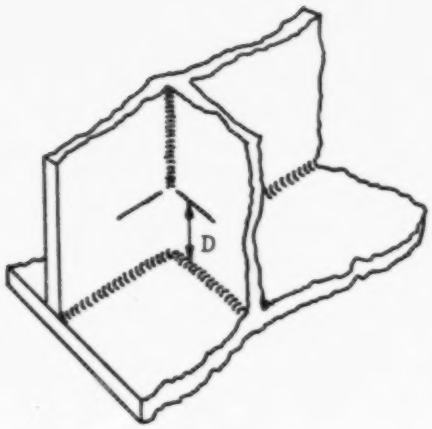

D approx. 150 mm

- To reduce restraint at critical areas, such as corners, leave a portion of the connection between less restrained components unwelded until the critical welds are completed, as indicated by 'D'.

6.3.5.6 Intermediate Stress Relief

The use of intermediate heat treatment to reduce residual stresses has not been particularly successful in controlling lamellar tearing. Large members which cannot be placed in a furnace require localized heating which can increase the contraction strains during cooling. Heat treatment may cause additional decohesion of inclusions in susceptible material, thereby increasing the indications of lamellar tears during subsequent ultrasonic inspection.

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7. DETECTION AND REPAIR OF LAMELLAR TEARING AFTER WELDING

7.1 When Is Non-Destructive Testing for Lamellar Tearing Recommended?

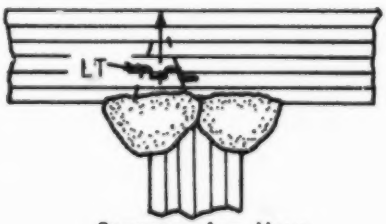
Normal weld inspection requirements and procedures are adequate where the risk of lamellar tearing is small. However, where the risk of tearing is significant because of the combination of material properties, welding procedures and joint configuration, additional test methods for the detection of lamellar tears should be employed. For members and joints which are critical to the overall integrity of the structure, such as the node joints and deck to leg connections of offshore jacket type structures, supplemental testing is recommended.

7.2 Which Non-Destructive Testing Methods Are Applicable?

Standard non-destructive testing methods such as visual inspection, dye penetration and magnetic particle inspection are satisfactory for surface cracking but not for sub-surface tears. Radiography is generally not practical for the detection of sub-surface tears since the inclusions in the plate can mask defects and it is difficult, if not impossible, to direct radiation along the tear axis. Of all the conventional non-destructive testing methods, ultrasonic testing is the most practical and widely used technique for detecting lamellar tears.

7.3 Ultrasonic Testing (UT) Of Welded Joints

The pulse-echo ultrasonic testing technique is based on the interpretation of reflected ultrasonic waves from the fracture surface to detect lamellar tears. The instrument probe is both transmitter and receiver. The ultrasonic beam is reflected either by the face plate opposite the one on which the probe is applied (bottom echo), or partly at least by an area of lamellar tearing or any other defect of the metal (flaw echo). While UT methods normally locate plate and weld defects when the plate surfaces are flat and reasonably free from loose material, it is often difficult to distinguish true lamellar tears from inclusion bands and other forms of cracking. The materials that are most susceptible to lamellar tearing, such as thick plates with high concentrations of nonmetallic inclusions, contain the type of defects whch can attenuate the signals and make interpretation difficult. Misinterpreted ultrasonic indicators can often lead to unnecessary and costly repairs.



Compression Wave

Both compression wave and shear (or angle) probe UT methods are capable of accurately locating lamellar tearing. However, the usefulness of compression wave techniques is limited to T or corner joints.

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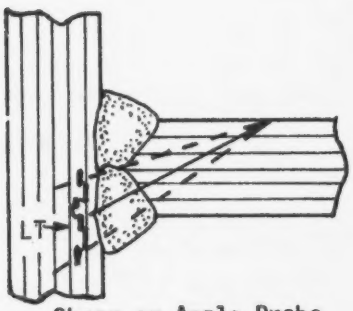

Shear or Angle Probe

Probe frequencies of 2 MHz are considered suitable for the rapid location of true tears. Sufficient resolution to obtain good identification of the characteristic stepped surface of the tear can be obtained by the use of 4 to 5 MHz probes. The use of higher probe frequencies together with high equipment gain settings are reported to increase the likelihood of erroneous indications of lamellar tears.

Details of technique and equipment for the ultrasonic detection of lamellar tearing are essentially the same as for the nominal UT inspection of welds. Specifics may be obtained in the American Bureau of Shipping Rules for Non-destructive Inspection of Hull Welds or ASTM E164 - Standard for Ultrasonic Contact Inspection of Weldments.

POINTS TO NOTE

- Ultrasonic testing should be specified for highly restrained welded connections, critical to the integrity of the structure, where the risk of lamellar tearing is significant.

- The reliability of the ultrasonic testing method depends to a great extent on the ability and experience of the operator. Personnel responsible for conducting ultrasonic tests should be familiar with the equipment being used and be properly qualified by training and experience to perform the necessary calibrations, and to interpret and evaluate indications in accordance with the terms of the specification. In addition to being qualified in accordance with the requirements of the American Society of Non-destructive Testing Publication TC-1A - Supplement C, Ultrasonic Testing Methods or other recognized agencies, the personnel should preferably have experience in, or be able to demonstrate ability to identify, lamellar tears.

- Ultrasonic testing should be performed when all welding on the joint is completed and maximum restraint is reached. Since lamellar tearing has been reported to occur up to 36 hours after the completion of all welding and the cooling of the component, final ultrasonic inspection of critical joints should be performed no sooner than 36 hours after welding on the joint is completed.

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- All critical welded joints, such as the node joints and deck to leg connections of offshore structures, should be ultrasonically inspected.

- Acceptance standards for lamellar tearing should be established so that clusters of inclusions and dense microstructural bands which appear as defect indications do not constitute rejectable defects. Since the removal and repair of minor non-critical tears may do more harm than good, the acceptance criteria should consider the functional requirements of the component or joint as well as the practical level of workmanship which experience indicates can be obtained in weldments of a given type. At present, the welding acceptance criteria of marine classification societies and national codes and specifications do not contain specific acceptance standards for lamellar tearing.

- In order to distinguish lamellar tears from pre-existing defects (large inclusions, laminations, etc.), the base material in the area of the weld should be ultrasonically inspected prior to fabrication. These inspections should be methodically performed and recorded using a grid system for locating check points.

- Ultrasonic indications of lamellar tearing exhibit a characteristic multiple peak signal and a rapid change in depth as the probe is moved. These characteristics help to differentiate lamellar tears from other cracks, laminations or backwall reflection.

7.4 Repair of Lamellar Tears

The repair of lamellar tears can be difficult, time consuming and costly; and, in the case of highly restrained connections the repair can be more detrimental than the original weld. The increased risk of lamellar tearing during repair is partially due to the greater overall restraint of the completed structure. The mechanical and thermal strains induced by the repair welding can cause tearing to occur at a greater depth below the original weld fusion line. The basic methods of repair are:

- gouging out of the tear and replacement with weld metal

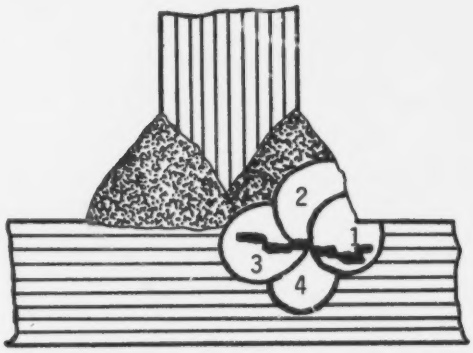
- cutting out the defective material and replacing with material with improved through-thickness properties. This procedure is often accompanied by modifications to the welding procedures or joint details in order to avoid the conditions which precipitated the original tear.

- providing additional structural members to carry the anticipated service loads across the joint.

Prior to selecting a repair procedure, it should be verified that the discontinuity is a lamellar tear. The number, location and extent of other tears, if any, should also be determined. If the crack is in fact a lamellar tear and exceeds the specified acceptance standards, all the factors which can contribute to the development of lamellar tears, namely material susceptibility, joint configuration and welding procedures, should be reviewed. Merely gouging out the tear and rewelding using the original joint geometry and welding procedures under conditions of possibly even higher restraint, will probably result in new lamellar tears. For this reason, it is often more economical to replace a component or joint rather than to repair it. Alternately, additional support members can be provided to reduce the service loads across the joint, thus reducing the criticality of the joint.

Where gouging and rewelding is judged acceptable, the following procedures should be used:

- Remove damaged material using flame gouging, arc-air gouging or grinding. The Australian Welding Research Association reports that flame gouging is slightly preferred to arc-air gouging due to the less intense thermal gradients and lower thermal induced stresses of flame gouging [1]. On the other hand, a fabricator with LT repair experience reports that gas gouging develops too much heat in the weld causing the lamellar tear to propagate [7]. He recommends using only arc-air gouging with no preheat. Grinding is slow and impractical.



- Flame Gouging - the first pass of the gouging torch should cut across the end of the plane of tearing at such an attitude as to minimize the tendency of the tear to open up as well as to release any tensile stress across the tear. The base of the gouge should be well rounded. Subsequent passes should remove 2 to 3 mm of the material below the original tear and 3 to 4 mm beyond the ends of the tear. Deeper and wider gouging will increase the amount of rewelding with a corresponding increase in the risk of new tearing. In some cases, complete release or disassembly of the welded joint may be required.

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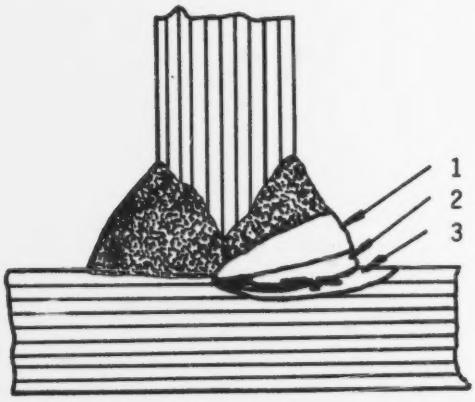

- Air-Arc Gouging - the first arc-air gouge should be made adjacent to the tear and extend 3 to 4 mm beyond the end of the tear. Additional passes should be made parallel to the initial gouge until material 2 to 3 mm below the original tear has been removed.

- Regardless of the gouging method, all final surfaces should be lightly ground and inspected using magnetic particle or dye penetration testing methods prior to welding.

- Buttering layers of low yield strength weld metal are generally considered essential prior to making connecting welds. The welding procedures given in Section 6.3 should be employed in order to reduce strains in the through-thickness direction. It is recommended that the minimum preheat temperature be maintained for 8 hours after all welding on the joint is complete.

- The repaired joint should be thoroughly re-examined in accordance with the requirements for ultrasonic testing given in Section 7.3.

NOTE

During the repair process, the actual location of the lamellar tear should be noted and compared with that indicated by the ultrasonic test in order to validate the testing procedures.

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8. TESTS FOR DETERMINING THE SUSCEPTIBILITY OF STEEL PLATES TO LAMELLAR TEARING

During the last fifteen years, many tests have been developed for determining the susceptibility of different grades of steel plate to lamellar tearing. With varying success, these tests attempt to provide reproducible results which correlate well with known cases of lamellar tearing. Each test incorporates different combinations of the actual joint design, component and joint restraint, welding procedures, and material properties. The difficulty in devising a single, universally acceptable test procedure reflects the fact that, while it is practical to represent to some degree the actual geometry and fabrication procedures, the test material may not be representative of the material used in the production joint. The through-thickness properties of individual plates are variable because of the irregular distribution of nonmetallic inclusions in the plate. The more important tests are listed below by type:

- Nondestructive Tests (without welding)

  (i) Ultrasonic inspection of susceptible steel plates prior to fabrication [8] - of limited usefulness in determining the susceptibility of steel plates to lamellar tearing; useful for distinguishing lamellar tears detected during post-welding UT inspection from pre-existing defects.

- Destructive Tests Without Welding

  (i) Through-thickness tensile test - practical test; RAz gives good correlation with known incidences of tearing.

  (ii) Slice-bend test [9] - ground surface is examined for the size and location of cracks after the specimen is subjected to increasing surface strains; practical test which produces realistic tears.

  (iii) Special notched tensile test [10] - compares the shear fracture loads on and across the laminar plane; for preliminary screening of susceptible material.

  (iv) Charpy V-notch impact test [11] - limited usefulness; can be used only for plates 55 mm thick or greater.

  (v) Microscopic count of nonmetallic inclusions - uses standard metallurgical examination procedures to determine number, size, shape and distribution of nonmetallic inclusions; impractical for production test; more suitable for research.

- Destructive Tests With Welding

  (i) Welding Institute window test [12,13] - specimen of the susceptible base material is inserted through a rectangular hole or window in a restraining plate and welded to form a cruciform joint; observed tearing can often be induced by root cracking not lamellar tearing; restraint level varies with jig and test plate thickness; not practical for production use.

  (ii) Cranfield test [14] - a stem plate is beveled to 45 or 60 degrees and multirun welded to the steel sample to be tested; severe test conditions are only capable of identifying materials with a high resistance to tearing; mixed correlation with case histories.

  (iii) Short-transverse notched bend test [15] - complex and expensive test more suitable to research.

  (iv) Lehigh restraint test [2] - suitable for quantitatively measuring lamellar tearing susceptibility under laboratory conditions.

  (v) H-type restraint test [16] - research oriented test.

  (vi) Tests of prototype welded joint - difficult to duplicate the exact restraint levels and welding condition present during actual production; does not take into account the variability of properties in the through-thickness direction; not practical for production testing.

With the increasing use of RAz by the major ship classification societies to define and approve Z-grade steels for the use in ships and offshore structures, RAz, as measured by through-thickness tensile test, is quickly becoming the standard test for determining the susceptibility of steel plates used in the marine industry. To date, a standard RAz test procedure has not been adopted by the different classification societies. While similar in theory, all of the currently published RAz test procedures differ slightly in the required dimensions and configuration of tensile-test specimens. Fabricators and steelmakers should follow the specific requirements of the cognizant classification society rules while keeping in mind the following additional considerations:

- The RAz acceptance limits shown in Section 6.2 are appropriate for materials with yield strengths less than 40.8 kg/mm^2 (58,000 psi).

- Because of the small cross-sectional area of material being tested, the use of six specimens will give a statistically better sampling than the three samples required by some rules.

- The results can be greatly influenced by single large inclusions or clusters.

- RAz values are strongly influenced by the diameter of the test specimen. Smaller diameter specimens are influenced by the size and position of large inclusions which decrease minimum values while increasing maximum values. Larger diameter specimens have more lateral restraint which lowers the mean values and reduces scatter. Accordingly, care must be exercised in comparing RAz values obtained from different sources or test procedures.

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APPENDIX A

MECHANISM OF LAMELLAR TEARING

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Australian Welding Research Association
from Appendix A of AWRA Technical Note 6,

References for Appendix A are listed at the
end of the Appendix.

A-1 BASIS

Lamellar tearing occurs when tensile stresses and strains applied to the material in the through-thickness (Z) direction of the steel exceed the ability of the steel to withstand these stresses and strains, and there are sufficient inclusions present to result in the typical LT fracture.

Alternatively stated, lamellar tearing occurs when the steel properties are inadequate to withstand the stresses and strains in the Z-direction.

A-2 STEEL PROPERTIES

.1 Anisotropy. An inherent feature of wrought steel products is the differences which can occur in properties in different directions, ie. the steel is anisotropic; although for most applications it can be treated as isotropic. This anisotropy is brought about by the rolling or forging operations which mainly flatten inclusions and may modify the metallurgical structure of the steel.

.2 Mechanical Properties. Mechanical properties in the Z-direction usually are reduced to a varying degree. The tensile strength and ductility (as measured by reduction of area or % elongation) are most affected. In exceptional cases tensile strength may be reduced by 30% and ductility to virtually zero. Yield or proof stress is hardly affected except when inclusions are gross.

.3 Cause. The Z-direction properties are reduced as a result of:

(a) increase in maximum and average length and width of inclusions.

(b) increased number of inclusions and closer spacing.

(c) increased alignment of inclusions on planes.

This effect has been established by theoretical work using fracture mechanics and proven by testing.

These properties may also be reduced by:

(d) hydrogen from welding operations or parent metal;

and as more recently reported (Ref A1) by:

(e) the temperature and stress cycles leading to strain ageing or similar effects; and

(f) prior cold work leading to exhaustion of ductility and possible strain ageing effects in the matrix between inclusions.

A-3 THROUGH-THICKNESS TENSILE STRESSES AND STRAINS

.1 Cause. These stresses and strains result from:

(a) weld and parent metal contraction on cooling after welding,

(b) restraint of the joint components, ie external resistance to contraction,

(c) other thermal or load influences, eg. uneven preheat; and from

(d) the Poisson effect due to high longitudinal stresses along the weld resulting in high triaxial stressing.

.2 Location of Mechanical Strains. Tensile stresses and strains vary across and along the welded joint, and maximum values may be located:

(a) at extreme weld runs such as under the root or toe (last run) as in Fig. A-1a. Load diffusion and strain across the plate will be concentrated in these areas because of the notch or stress concentration, particularly if any bending moment is involved, as with single sided or unbalanced welding.

(b) in the central plate area as in Fig A-1b, often when this is more susceptible than near the surface.

(c) at weld or material defects or poor weld or penetration shape. These can act as severe stress and strain concentrators - see Figs A-1c-e.

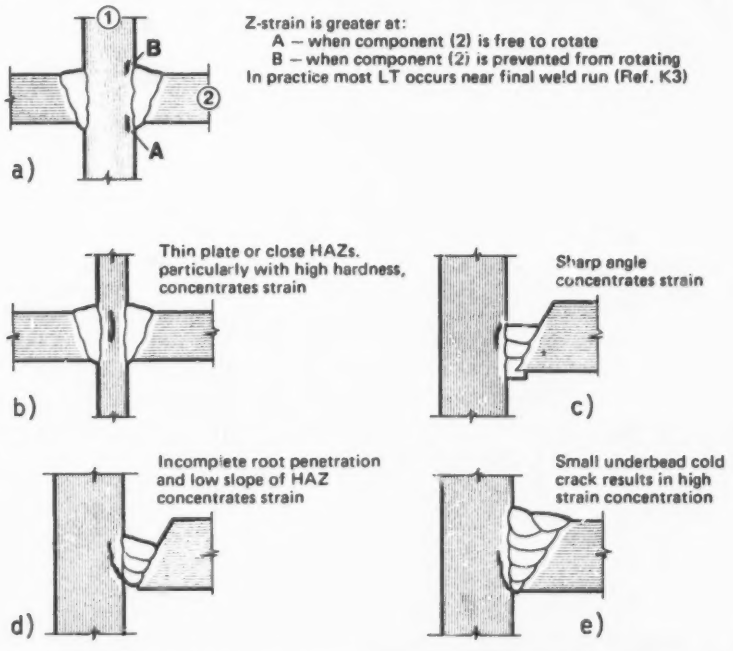
Z-strain is greater at:
A – when component (2) is free to rotate
B – when component (2) is prevented from rotating
In practice most LT occurs near final weld run (Ref. K3)
1
2
B
A
a)
Thin plate or close HAZs. particularly with high hardness, concentrates strain
b)
Sharp angle concentrates strain
c)
Incomplete root penetration and low slope of HAZ concentrates strain
d)
Small underbead cold crack results in high strain concentration
e)

Fig A-1 Location of maximum strain in Z-direction.

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(d) just outside the visible HAZ, particularly where the HAZ boundary is parallel to the plate surface. This part of the parent metal almost always has lower yield stress than the HAZ or weld metal at the temperatures where LT occurs.

Weld and parent metal contraction increases as the weld width, volume and number of runs increase.

A-4 FRACTURE

It is believed that fracture or tearing occurs in the stages shown diagrammatically in Fig 10 (from AWRA Technical Note 6 dated April 1976), ie:

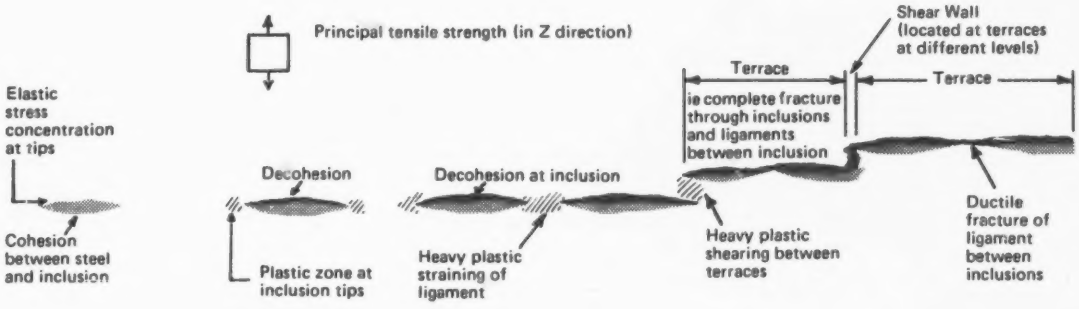

Fig 10 Mechanism of LT.

.1 On first encountering significant stress - almost certainly within the elastic range, decohesion occurs at the inclusion/matrix interface. The stress required will be dependent on the type and shape of inclusion and the microstress system developed.

.2 At the same time at the tips or ends of inclusions and other adjacent defects, plastic deformation occurs first at the larger inclusions or those so closely spaced that there is interaction between the two, i.e. where the spacing is less than about the size of the larger inclusion.

.3 On further straining due to further cooling or most likely due to further welding runs, the ligament between the inclusions becomes fully plastic and the voids at inclusions increase in size generally by ductile tearing.

.4 With additional straining, the extended voids link up in planes of general weakness, ie where the inclusions are aligned; and the "terrace" is formed - see Fig A-2. Fig A-3 shows the nature of the terrace surface.

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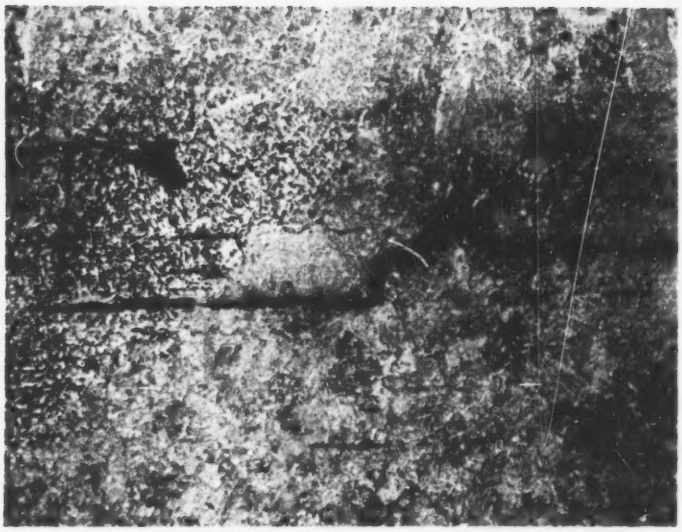

Fig A-2 Linking up of voids to form terraces X50.

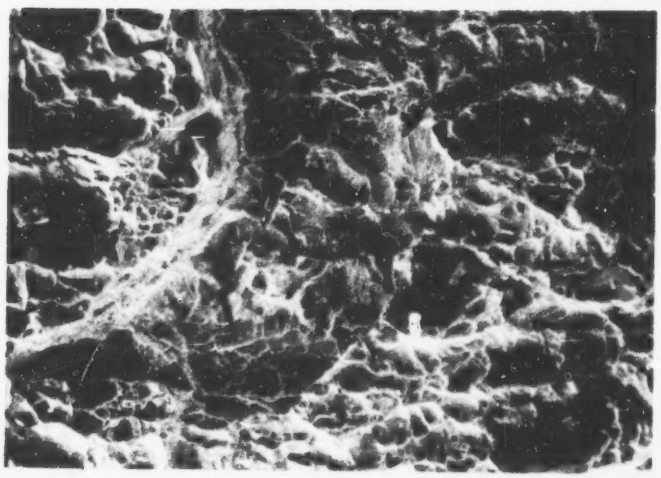

Fig A-3 Fracture surface of terrace showing ductile fracture and inclusions X100.

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.5 Slightly further straining connects the terraces on different levels by ductile shearing of the "walls", virtually to give complete separation. See Figs A-4 and A-5. Shear walls in lamellar tearing are smaller than in mechanical tests.

.6 If the material forming the ligament between inclusions has exceptionally poor properties, ie. low plane-strain fracture toughness (K_{1c}) or low critical crack opening displacement (δ_c), these areas may show areas of brittle fracture.

.7 The role of hydrogen is not clear, but probably accentuates local stress at void tips, ie a position to which hydrogen preferentially diffuses. Hydrogen has been shown experimentally to have a greater effect on LT in steels with higher carbon equivalent. This is most likely due to the increased risk of underbead (or cold) cracking, which even if on a microscale may trigger off LT.

.8 For LT to occur, the connection system must have considerable strain energy and be able to transfer this to the area of tearing.

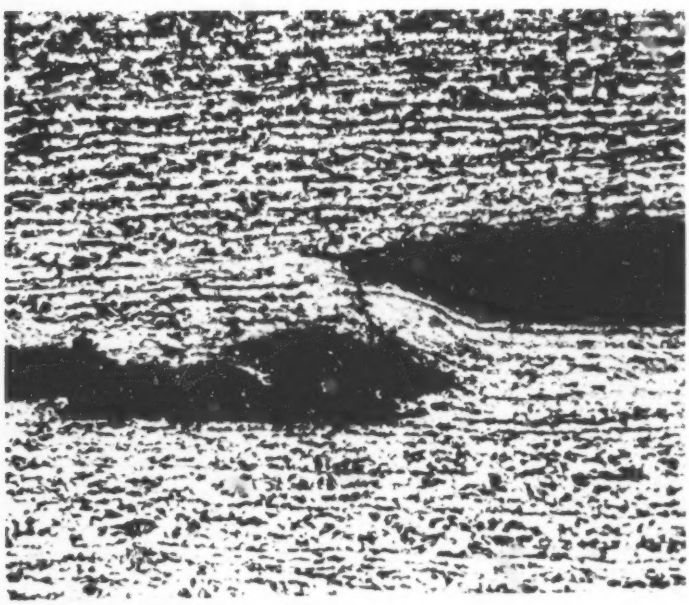

Fig A-4 Small shear wall linking closely aligned terraces X150.

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Fig A-5 Electron scanning micrograph giving 3-dimensional view of shear wall X200.

LIST OF REFERENCES FOR APPENDIX A

A1 Takeski, Y., "Lamellar Tearing and Marine Structures", Welding and Metal Fabrication, December, 1975.

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APPENDIX B

ORIGINS OF INCLUSIONS

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References for Appendix B are listed at the
end of the Appendix.

B-1 GENERAL

LT occurs in parent material and hence is greatly influenced by the material properties. LT is also highly directional sensitive and dependent on through-thickness direction properties.

These properties and the risk of LT depend:

(a) primarily on inclusions in steel; but also on

(b) the steel matrix itself.

The effect of inclusions on properties has been noted in 2.3 of Appendix A. The various types of inclusion, their origin in steelmaking and modification in rolling are discussed below, together with the use of various material properties in assessing the susceptibility of steel to LT.

B-2 INCLUSIONS

In constructional steel plates and sections, typical nonmetallic inclsions are:

.1 Sulphides, mainly manganese sulphide (MnS) which may be:

(a) Type I, ie. ellipsoidal or spherical in shape. These are usually small in size and are seldom responsible for LT.

(b) Type II, ie. flattened lamellar shape as in Fig B-1a. These are often a major factor in LT, particularly when elongated in stringers. They are predominant in aluminum treated silicon killed steels.

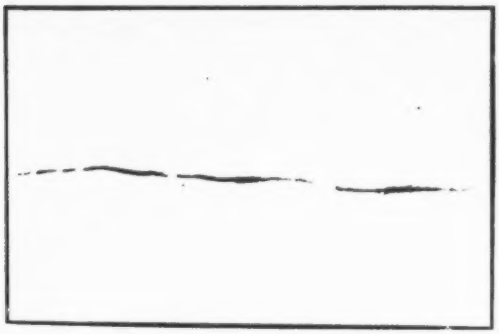
Other sulphides include the rare-earth metal (REM) sulphides and oxysulphides which are found in steels specially treated to give high RAz. These sulphides are predominantly spherical in shape - see Fig B-1b.

.2 Silicates, metal-silicon-oxygen compounds. In the stringer form, as in Fig B-1c, these have a dominant effect, particularly when RAz is less than 15% (Ref B1).

.3 Aluminates, Al_2O_3 or complex aluminates.

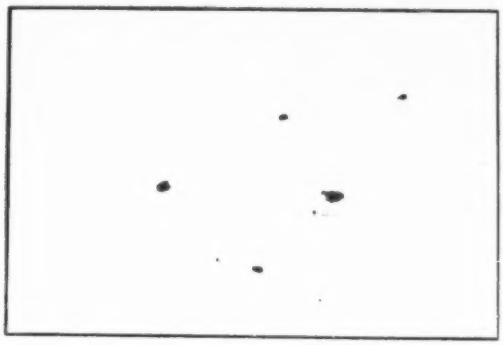
.4 Mixed types, generally combinations of sulphides and silicates (see Fig B-1d) which often are relatively short.

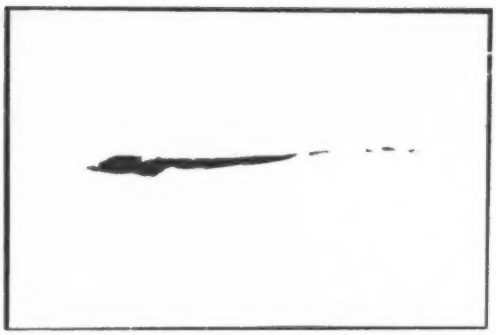
While silicate stringers and Type II sulphides have greatest effect on RAz, all inclusions may be involved in LT.



a) Type II sulphide stringer (in C-steel, Si-killed, Al-treated, with 3% RAz).

b) REM sulphide and oxy-sulphide (in C-Mn-Nb steel, Si-killed Al and REM treated, with 65% RAz).





c) Silicate stringer (in C-Mn steel, semi-killed, with 8% RAz).

d) Duplex stringers, Mn-S surrounded with silicate tails (in C-Mn steel, semi-killed with 50% RAz).

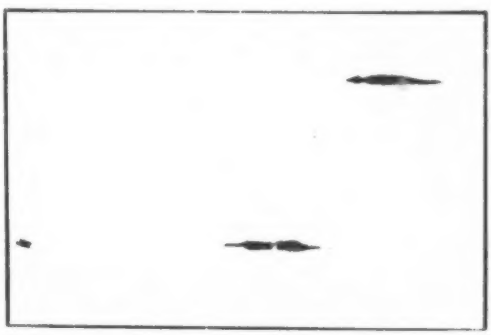


Fig B-1 Micrographs of typical inclusions X400.

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B-3 ORIGIN OF INCLUSIONS

.1 Steelmaking Controls. Inclusions exist in all steels to some extent and originate in steelmaking from impurities in raw materials and from gas reactions.

Near the final stage of steelmaking, either in the basic oxygen furnace or after pouring into ladles from open hearth or electric steelmaking furnaces, the general composition of the steel is largely fixed. Control of steelmaking operations to this stage enables, for instance, sulphur - the cause of MnS inclusions - to be limited frequently to less than 0.02% in normal constructional steels. Special control sometimes enables 0.01% to be achieved - a level where the risk of LT is greatly reduced.

Further steelmaking operations which have an important effect on the type, distribution and geometry of inclusions may include:

(a) de-oxidisation, and

(b) sulphur control.

.2 Steelmaking Process. Different processes appear to have no important effect on inclusions which promote LT.

.3 De-oxidisation. This operation improves properties by reducing oxygen content, and is carried out by:

(a) addition of de-oxidants (ie "killing") to give semi-killed or fully-killed steels. This is the usual method adopted for controlling oxygen. Silicon and aluminum are the principal de-oxidants used.

In fully-killed steel, all oxygen in the ladle reacts with added silicon or aluminum to form oxides. In semi-killed steels, excess oxygen reacts with carbon to form carbon monoxide which is evolved during solidification of the ingot.

(b) vacuum degassing using special high capital cost equipment to remove gases including oxygen without the addition of deoxidants. This method reduces oxide-type inclusions and is used for special steels only.

.4 Final Sulphur Control. At the final stage of steelmaking sulphur can be further controlled by the addition of rare-earth metals (REM), eg. mischmetal, which contains cerium (Ce), or by calcium compounds such as hypercal.

This addition, which may also be made to the ingot -

(a) reduces sulphur level by removing sulphur through the slag, and

(b) ties up sulphur in REM oxy-sulphides which have high melting points, resist deformation during rolling and thus retain a globular, less harmful shape.

This method is now used for special steels where high RAz and resistance to LT is required.

.5 Ingot Pouring and Treatment. Further methods adopted by the steelmaker to reduce inclusions include:

(a) adjustment of pouring technique, and

(b) hot topping of ingots.

B-4 INFLUENCE OF ROLLING AND HEAT TREATMENT ON INCLUSIONS

.1 Basic Effect. After solidification, the ingot is reheated to a high temperature and reduced hot to slabs and then to plate or rolled sections. This deforms the originally globular inclusions to a flat and sometimes elongated shape - thus influencing RAz values and susceptibility to LT. The grains of the matrix are also elongated in the direction of rolling.

From the slab stage the change in shape of inclusions depends on:

(a) the degree of rolling or reduction in thickness,

(b) the direction of rolling, and

(c) the temperature of rolling.

Cropping at the slab stage removes the part of the slab containing piping, gross inclusions, etc.

.2 Effect of Thickness Reduction. With a greater degree of rolling and reduction of thickness, inclusions become flat and have more influence on RAz values.

.3 Effect of Rolling Direction. Rolling predominantly in the direction of the original ingot axis (ie straight rolling) elongates the inclusions into stringers.

Cross rolling, ie where there is rolling both transverse and along the ingot axis, lessens elongation and gives a rounder shape in plan. This leads to reduced RAz (Ref B2) but not necessarily increased susceptibility to LT.

.4 Effect of Rolling Temperature. This temperature is important as the plasticity of manganese sulphide inclusions relative to the steel matrix increases with decreasing temperature, while that of silicate inclusions decreases. Thus, the lower the temperature range of working, the greater the flattening of MnS inclusions. For further details see Ref B2.

.5 Influence of Heat Treatment. Modification to shape of inclusions is not possible by normal heat treatment. Diffusion annealing has helped, but is not practicable for constructional steels. Hence, there is no clear difference between as-rolled or normalised condition.

B-5 MATRIX FACTORS

.1 General. The effect of matrix properties on LT is probably small with usual constructional steels when inclusions are numerous and large. Research and experience suggest the matrix has more effect with few inclusions, but then the problem of LT is less.

.2 Grain Size. Experience shows that both coarse and fine grained steels can be susceptible to LT.

.3 Banding. Banding of rolled plate and sections is reasonably common, but this and other segregation of alloying elements do not appear to substantially reduce Z-direction properties or increase LT.

B-6 INFLUENCE OF INCLUSIONS ON PROPERTIES AND LAMELLAR TEARING

The effect of inclusion shape, distribution and size is discussed in 2.3 of Appendix A. Using this and the above information on various types of inclusions it is possible to give the very approximate relationships in Table B-6.

TABLE B-6 INFLUENCE OF INCLUSIONS

Inclusion Type	Decreasing risk of Lamellar Tearing / Increasing RAz	Steel Types Usually Involved
1. Silicate stringers	↓ / ↓	SK, FK-Si, FK-Si+Al
2. Type II manganese sulphide stringers	↓ / ↓	FK-Si, FK-S+Al
3. Duplex sulphides with silicate tails	↓ / ↓	SK
4. Ellipsoidal sulphides	↓ / ↓	FK-Si+Al (thick plate)
5. Spherical sulphides	↓ / ↓	REM treated steels

SK = Semi-killed
FK = Fully-killed
Si = Silicon killed
Al = Aluminum treated

B-7 REDUCTION OF AREA AS AN INDICATOR OF SUSCEPTIBILITY TO LT

.1 Selection of Reduction of Area. LT is clearly dependent on material properties, particularly in the Z-direction. It is natural that conventional, well-established mechanical tests have been used to check the material susceptibility. Through-thickness tensile tests of the material have been used extensively, and today they are used for specification purposes for special steels.

These tensile tests give yield stress, tensile strength, % elongation (on various gauge lengths) and % reduction of area (RAz). Variation of these properties is indicated in 2.3 of Appendix A and various researchers (Refs B3 and B4) have shown RAz to be the most discriminating and accurate material measure at the low ductilities where LT is encountered. It also has been found to correlate well with known LT incidence (Ref B5). This is not unreasonable as RAz is a measure of the local strain occurring at fracture and more nearly represents the behaviour in LT.

To ensure that the full thickness of material is assessed, standard practice today is to weld extension stubs to the plate by friction, stud or manual arc welding to provide grips for this tensile testing.

.2 Influence of Test Specimen on RAz. It is important to note that the test specimen diameter is significant in quoting RAz values as:

(a) the smaller diameter specimens are likely to be more influenced by the size and position of large inclusions, ie minimum values are reduced and maximum values increased.

(b) the larger specimens, up to approximately 20mm diameter, have more lateral restraint and thus give lower mean values and reduced scatter. Thus, 6.4mm diameter specimens give, in absolute terms, approximately 10% higher RAz means than 18mm specimens. See Fig B-2.

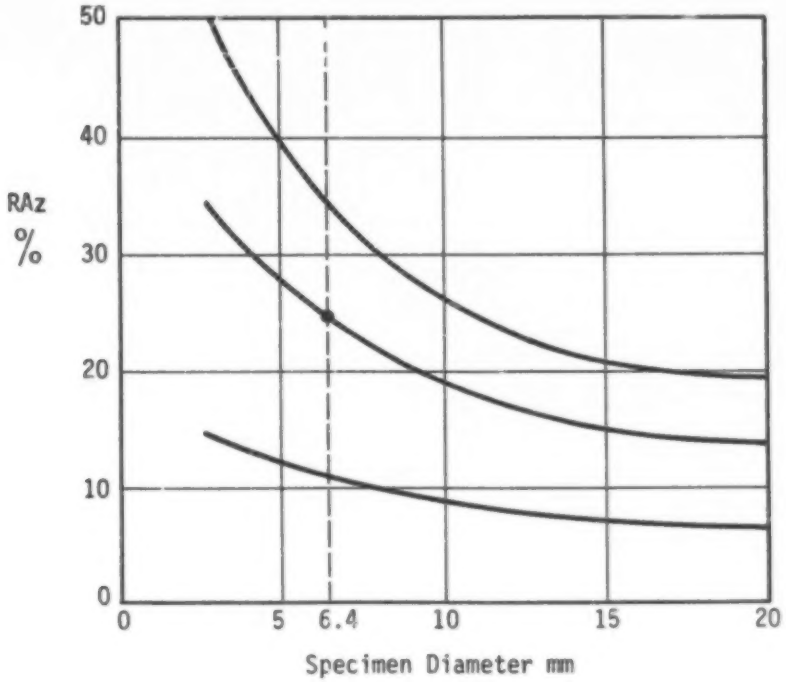

Fig B-2 *Typical effect of specimen diameter on RAz (for steel with approx. 25% RAz on 6.4mm ϕ). Refs* B5 *and* B10.

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.3 Variation of RAz in Thickness Position. Testing has shown that the maximum incidence of inclusions and fracture location may vary from just below the surface to the centre of the plate or section, but usually is more prevalent in the centre. Experience also indicates that plates may be more susceptible to LT at different thicknesses.

To provide for this, RAz tests check the full thickness.

.4 Variation of RAz in Plate. Investigations (Refs B1, B6 and B7) show no apparently consistent variation of RAz over various positions in the plate. The only general indication is that for the plates tested there was a slightly greater probability of lower RAz in the top central 30% of the plate.

.5 RAz Values to Reduce Risk of LT. Farrar (Ref B5) gives correlation of RAz with known LT, and indicates:

(a) in all steels which encountered LT, the mean RAz values (6.4mm diameter) were equal to or below 15% and the minimum values of all were below 12%.

(b) in all successfully fabricated steels, the mean values all exceeded 13% and the minimum values of all exceeded 5%.

At this stage it is not possible to state that steels with high values of RAz will not encounter LT, as much depends on restraint factors. As a guide, the values given in Fig B-3 are recommended. This data takes into account recommendations from:

- References B1 and B8,
- IIW, ie 15% to 20% minimum mean,
- Reference B9, 30% for node plates in offshore drilling rigs,
- Current practice, 25% minimum mean (4 or 6 specimens taken at the 1/4 plate width position) for most applications, (35% by one major oil company) and 10 or 15% individual minimum.

As the scatter can be high with small diameter specimens there is a risk that an occasional specimen will fail below the specified minimum. This will have little effect on LT, but should be allowed for by the usual retest clause.

B-8 EFFECT OF OTHER MATERIAL PROPERTIES ON DESIGN

The possible reduction of tensile strength and yield stress in the Z-direction may influence the design of the joint in addition to allowance for reduced RAz. These reductions are normally not great (see 2.3 of Appendix A) and can almost always be ignored in design.

Extensive service experience has indicated that conventional design which is based on X-direction properties is adequate. This is largely due to the following:

(a) steels with very low tensile or yield strength often will be detected by LT during fabrication, where conditions are more severe than almost all service conditions.

(b) tensile strength of most constructional steels in the worst condition in the Z-direction is greater than the yield stress on which most designs are based.

(c) in most welded joints there is diffusion of the service loads through a greater area - thus effectively reducing the stress; and

(d) the probability of all factors acting adversely is extremely remote.

In special critical cases where very high stresses are involved, special consideration may need to be given to design or material.

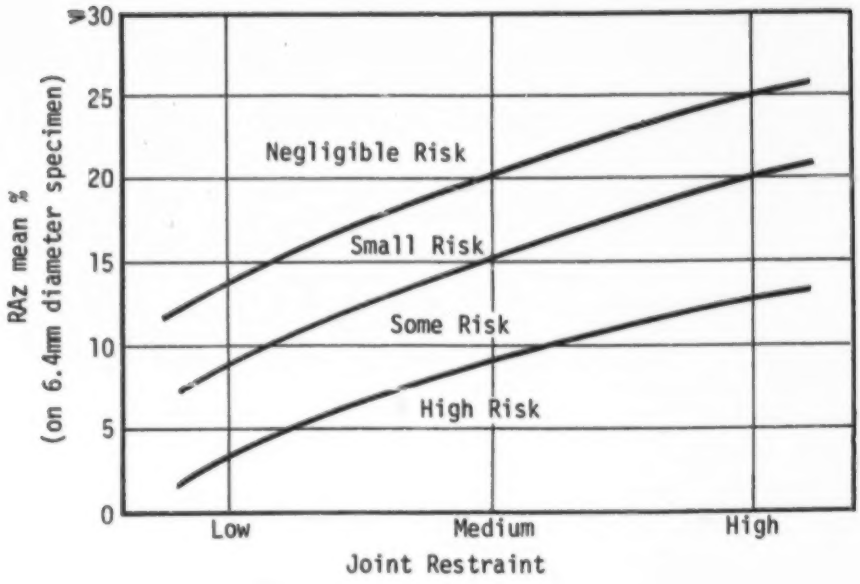

Fig B-3 Approximate Risk of Lamellar Tearing for C and C-Mn Steels. Specified minimum yield stress < 40.8 kg/mm^2

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SSC-276, *Fracture Behavior Characterization of Ship Steels and Weldments* by P. H. Francis, T. S. Cook, and A. Nagy. 1978. AD-A058939.

SSC-277, *Original Radar and Standard Tucker Wavemeter SL-7 Containership Data Reduction and Correlation Sample* by J. F. Dalzell. 1978. AD-A062394.

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